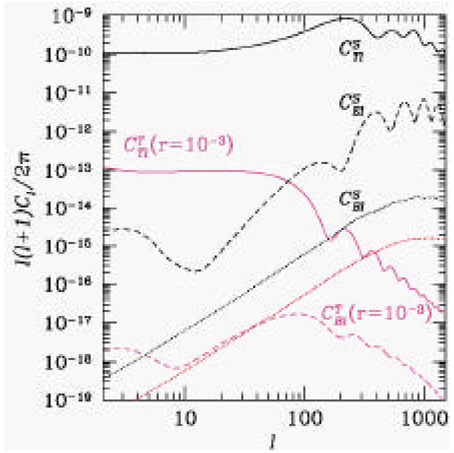
Measuring the Polarization of the **C**osmic **M**icrowave **B**ackground

CAPMAP and QUIET

Dorothea Samtleben, *Kavli Institute for Cosmological Physics, University of Chicago*

Outline

Theory point of view

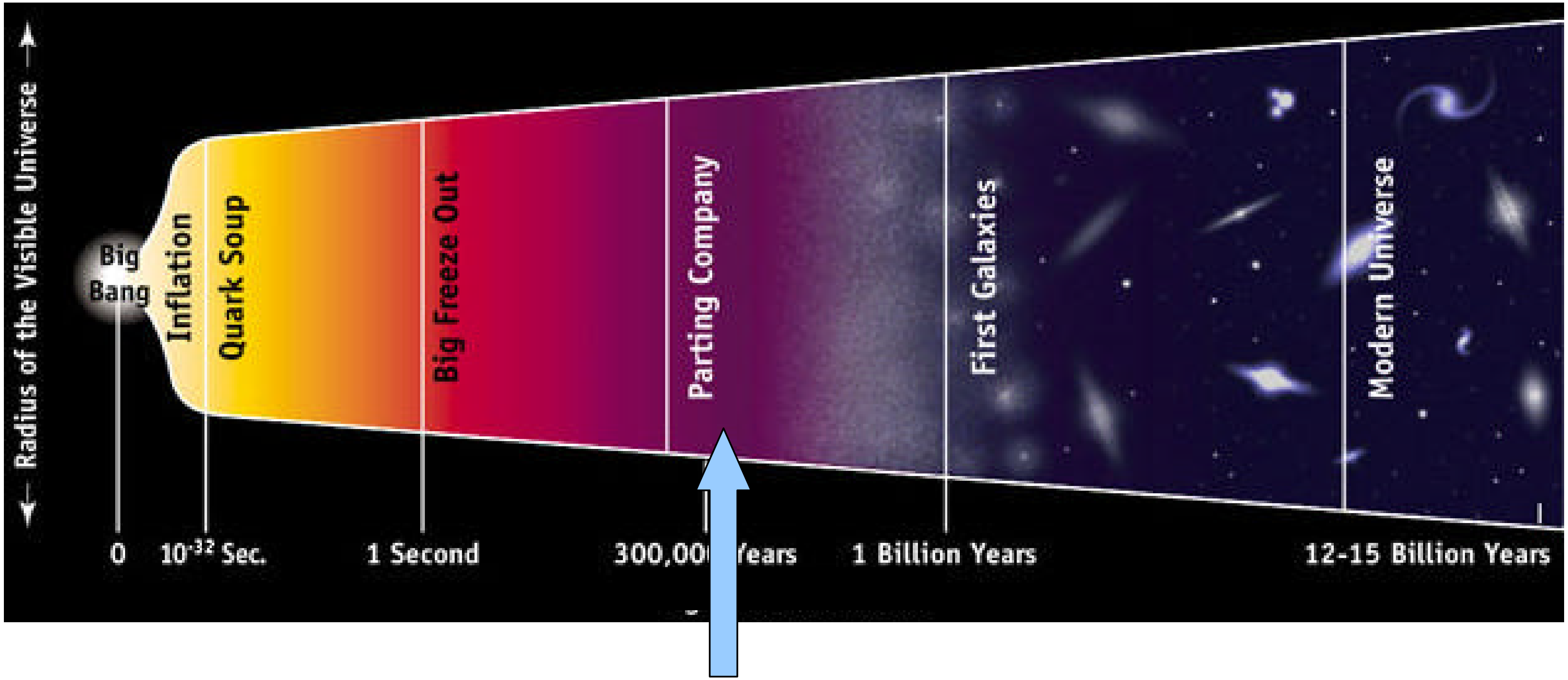


- What can we learn from the **C**osmic **M**icrowave **B**ackground (CMB)?
- How to characterize and describe the CMB
- Why is the CMB polarized?

Experiment point of view

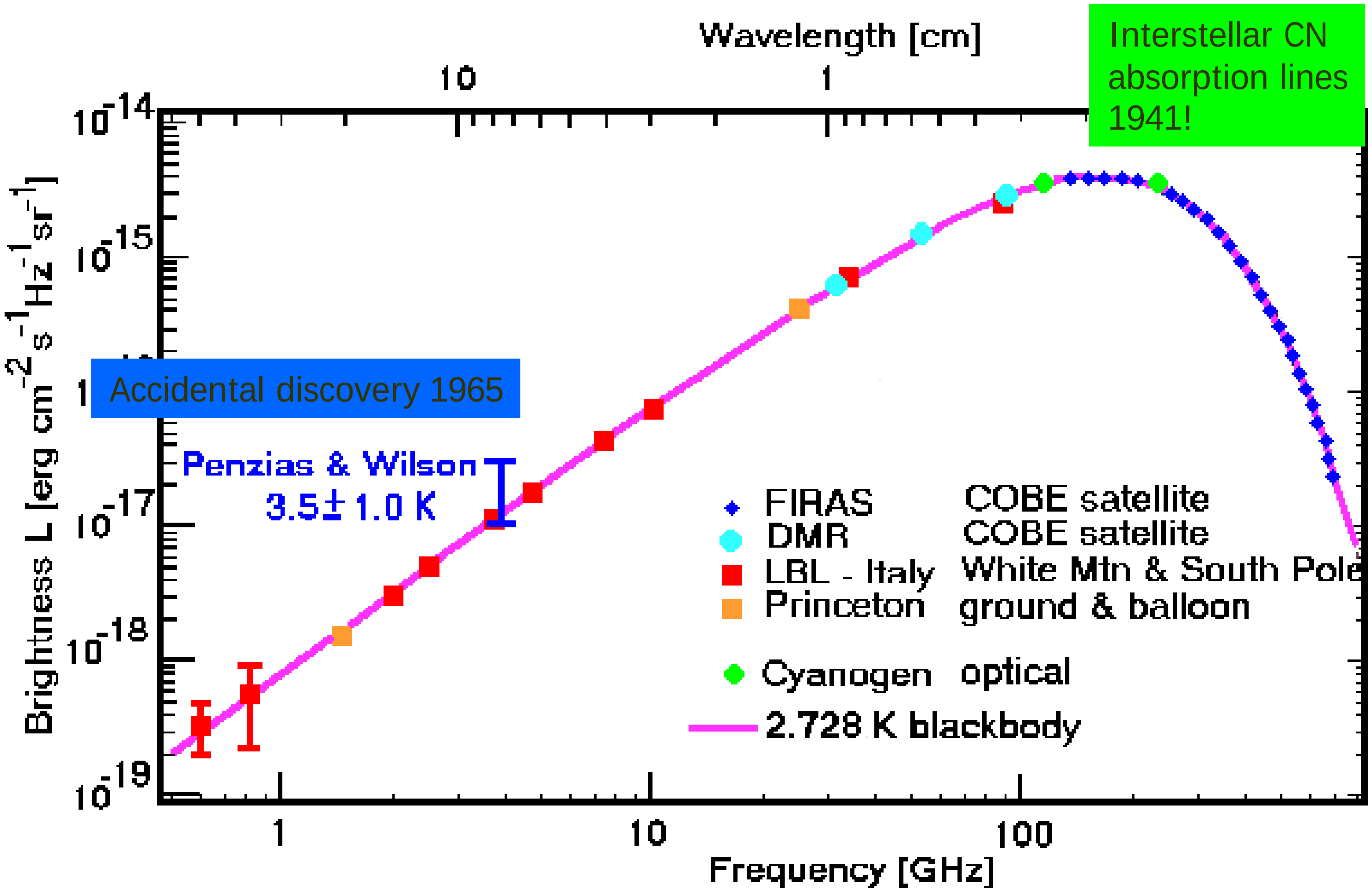
- CMB polarization experiments
- CAPMAP experiment, first results
- Future of CMB measurements
- QUIET experiment, status and plans

Where does the CMB come from?



- Temperature cool enough that electrons and protons form first atoms => The universe became transparent
- Photons from that ‘last scattering surface’ give direct snapshot of the infant universe
- Still around today but cooled down (shifted to microwaves) due to expansion of the universe

CMB observations



Blackbody Radiation, homogenous, isotropic

$\frac{\Delta T}{T} \leq (1-3)x10^{-3}$ (Partridge & Wilkinson, 1967)

WHY?

Rescue by Inflationary models

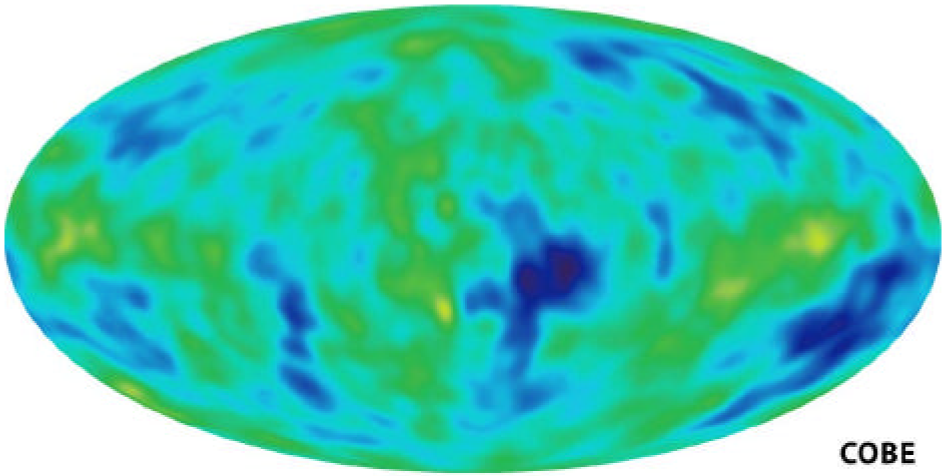
Inflation increases volume of universe by 10^{63} in 10^{-30} seconds

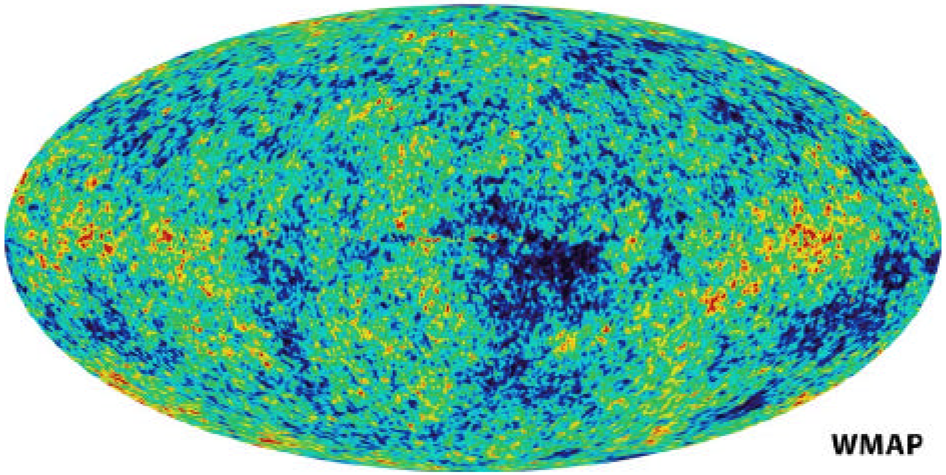
Consequences (observables) for CMB:

- Homogenous, isotropic blackbody radiation
- Scale-invariant temperature fluctuations
- On small scales (within horizon) temperature fluctuations from 'accoustic oscillations' (radiation pressure vs gravitational attraction)
- Polarization anisotropies, correlated with temperature anisotropies
- Gravitational waves, produced by inflation, cause distinct pattern in CMB polarization anisotropy
- Reionization period will impact the fluctuation pattern

→ Look for temperature and polarization anisotropies!

CMB temperature anisotropy map

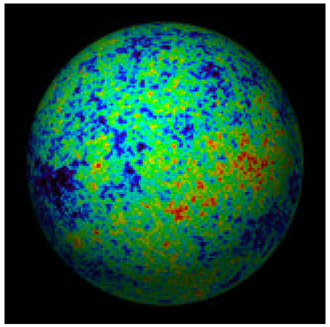




Temperature fluctuations (overall temperature, dipole and galaxy contribution subtracted)

COBE (1992)

WMAP (2003)



Pictures from NASA/WMAP Science Team

Description of anisotropies

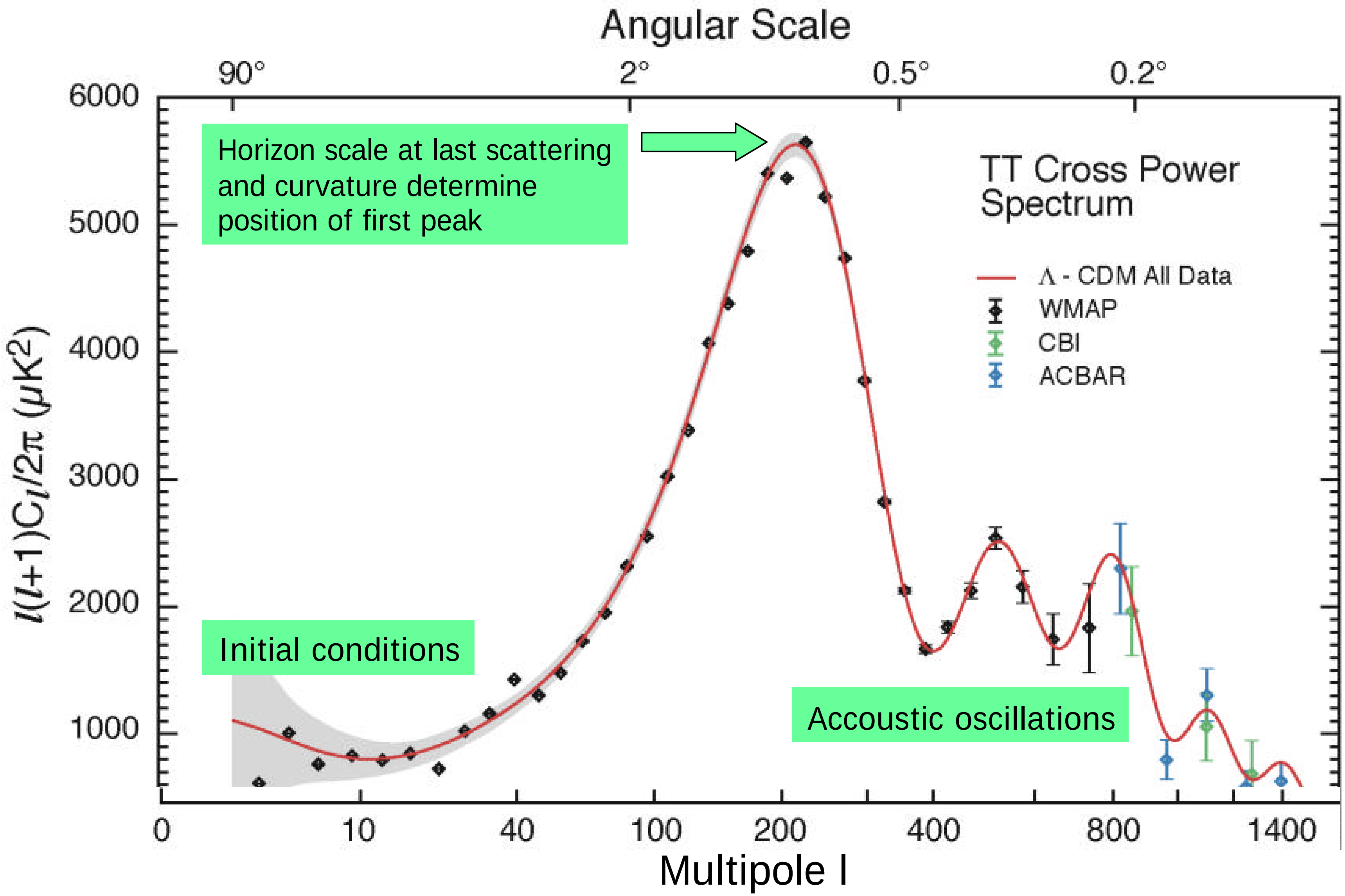
- Statistical properties of CMB predictable
- Representation by spherical harmonics Y_{lm}

Temperature: $T(q,j) = \sum a_{lm} Y_{lm}(q,j)$

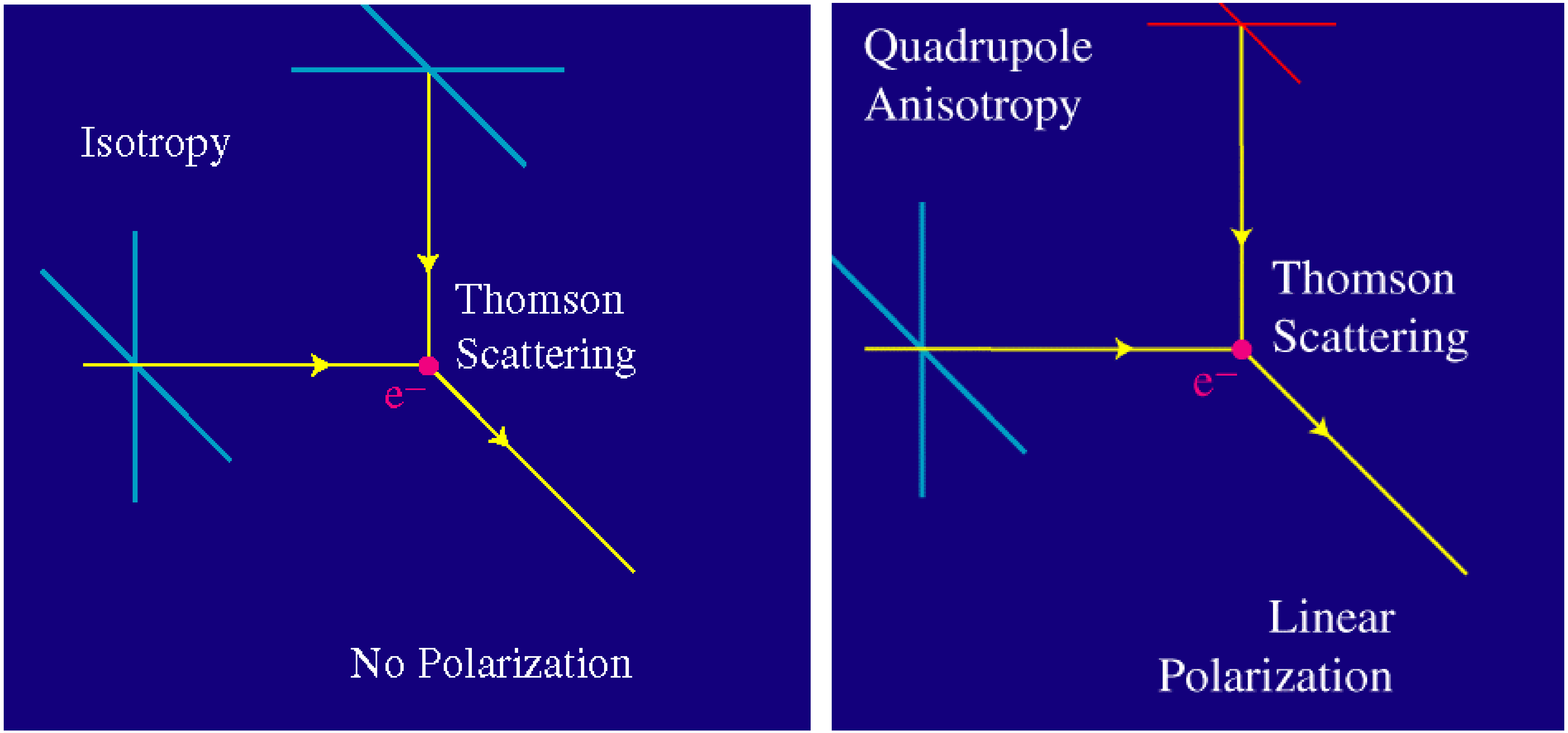
Definition for coefficients: $C_l = < a_{lm} a^*_{lm} >$

Variance (observable): $\Delta T^2 = \frac{l(l+1)}{2p} C_l$

WMAP temperature power spectrum

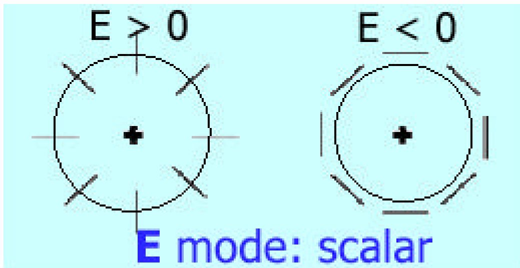


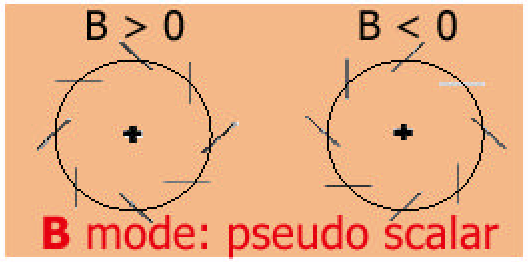
Why is the CMB polarized?



Different Polarization patterns

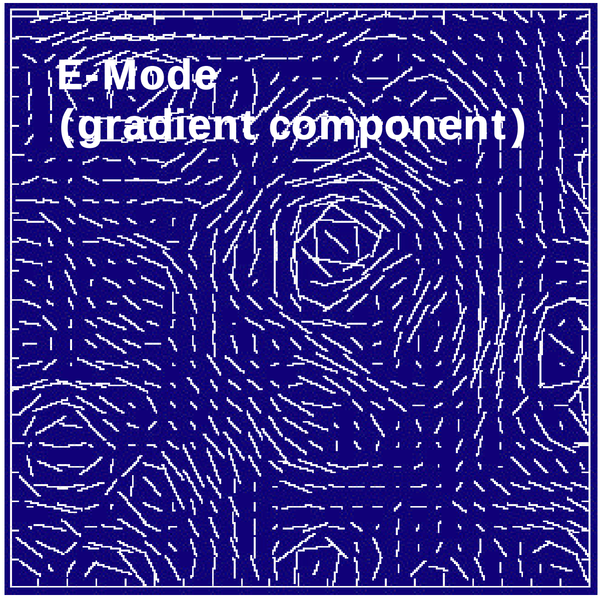
Division of Polarization into gradient (E-mode) and curl component (B-mode)

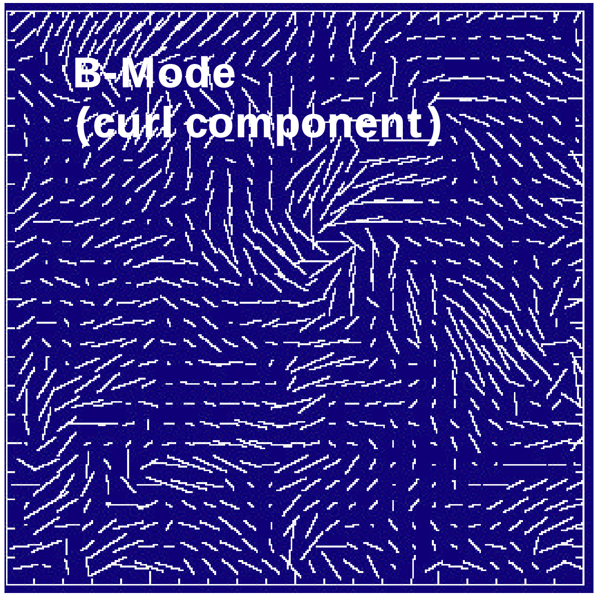




Density fluctuations	E-modes
Gravity waves	E- and B-modes, amplitude determined by energy scale of inflation (often linked to GUT scale)
Gravitational lensing	E-modes appear as B-modes

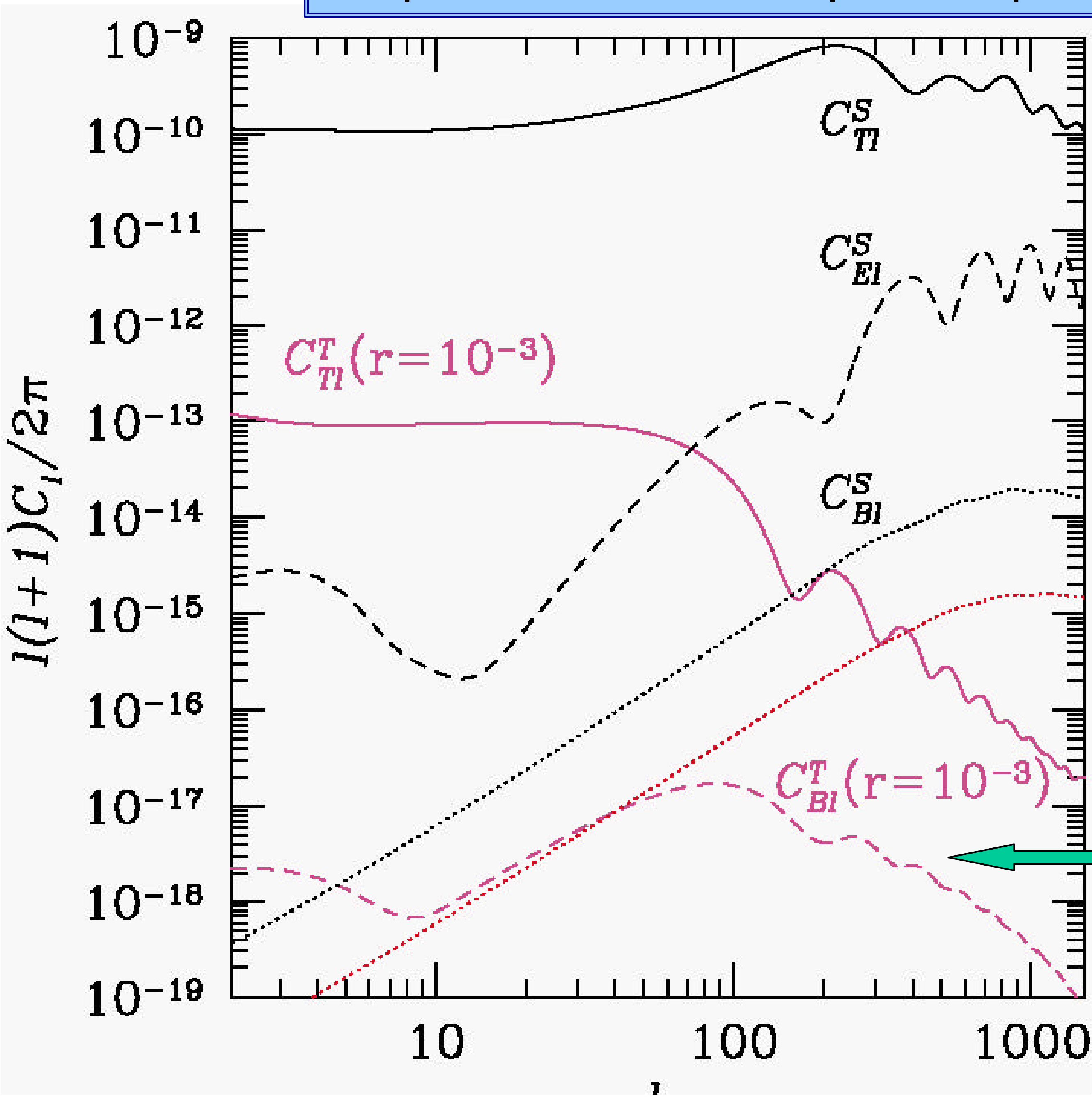
Different Polarization patterns





Density fluctuations	E-modes
Gravity waves	E- and B-modes, amplitude determined by energy scale of inflation (often linked to GUT scale)
Gravitational lensing	E-modes appear as B-modes

Expectations for the power spectra



TT spectrum

EE spectrum

E ->B lensing

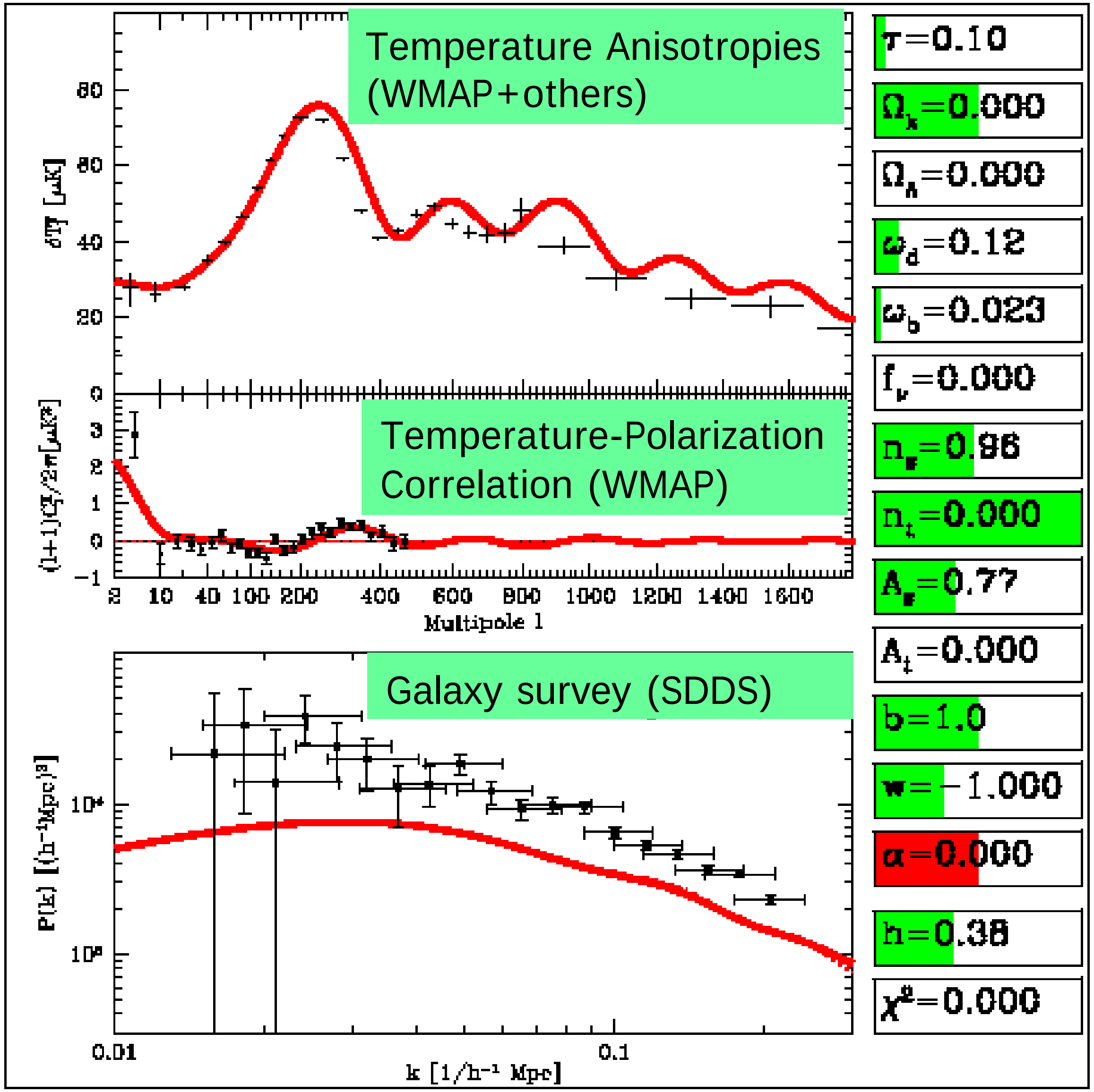
BB spectrum

Grav. Waves

$E_{inf} \sim 6x10^{15}$ GeV

(slow-roll Inflation)

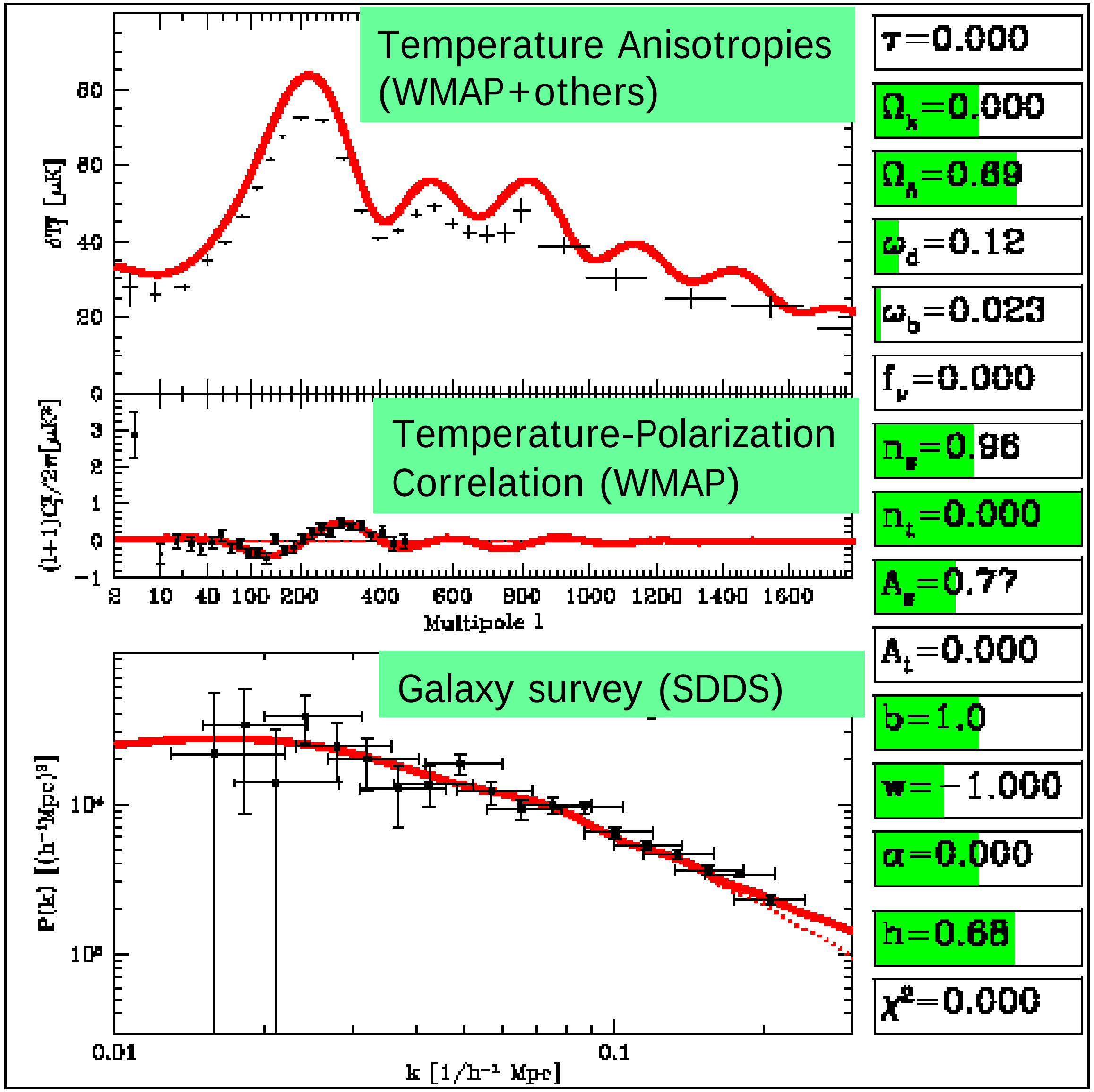
Cosmological parameter estimation from CMB measurements



- Shape of power spectrum determined by cosmological parameter values

Animation by M. Tegmark

Cosmological parameter estimation from CMB measurements



- Shape of power spectrum determined by cosmological parameter values
- Several parameters are degenerate: same spectrum shape compatible with different parameter sets.
- Other measurements necessary to unambiguously measure all parameters (Galaxy/structure surveys, Supernovae, BBN …)

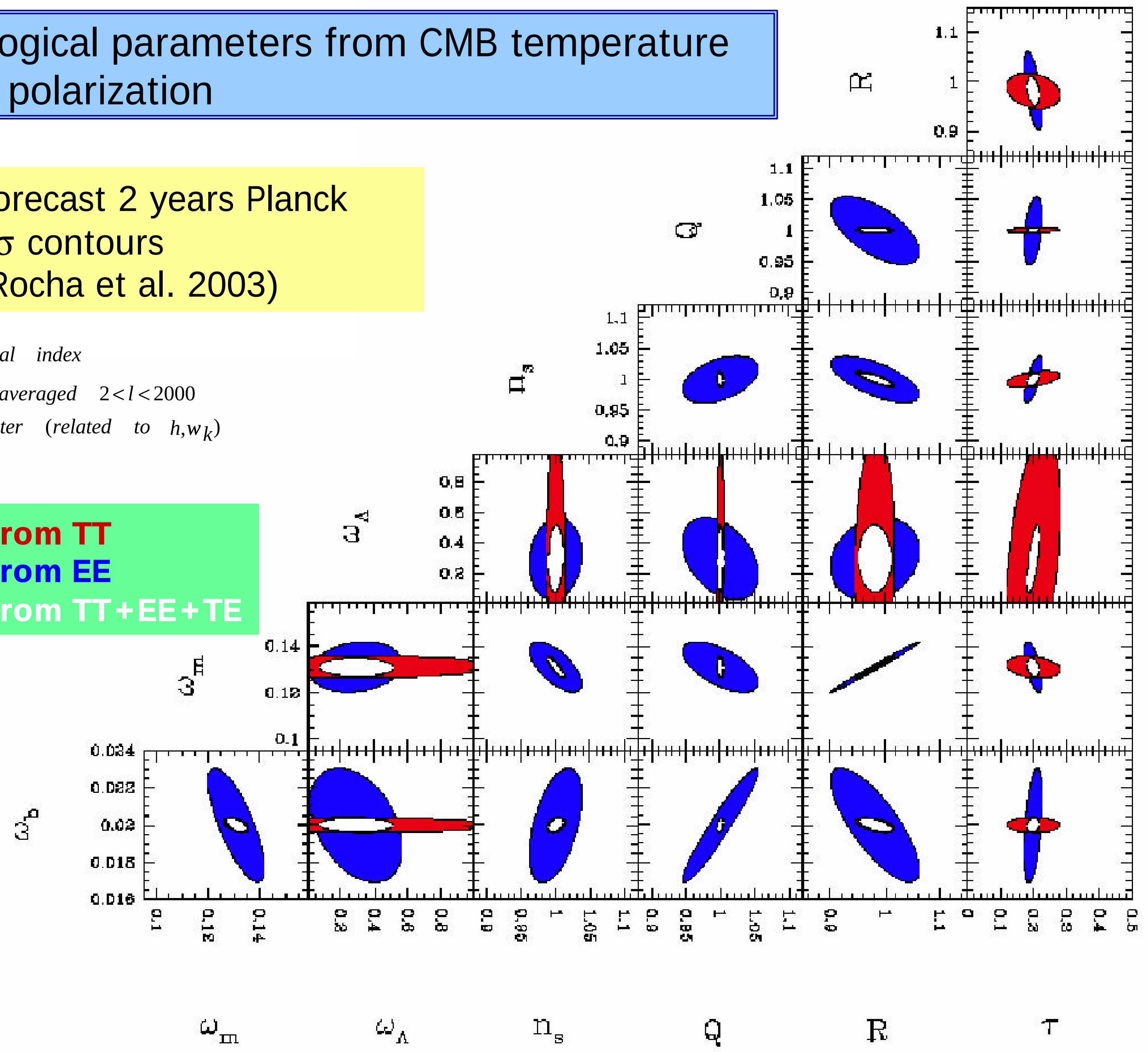
Animation by M. Tegmark

Cosmological parameters from CMB temperature and polarization

Forecast 2 years Planck
2σ contours
(Rocha et al. 2003)

$w_b = \Omega_b h^2$
$w_m = \Omega_m h^2$
$w_\Lambda = \Omega_\Lambda h^2$
n_s: *scalar spectral index*
$Q: \sqrt{<l(l+1)Cl>}$ *averaged* $2 < l < 2000$
R: *shift parameter (related to* h, w_k)
t : *optical depth*

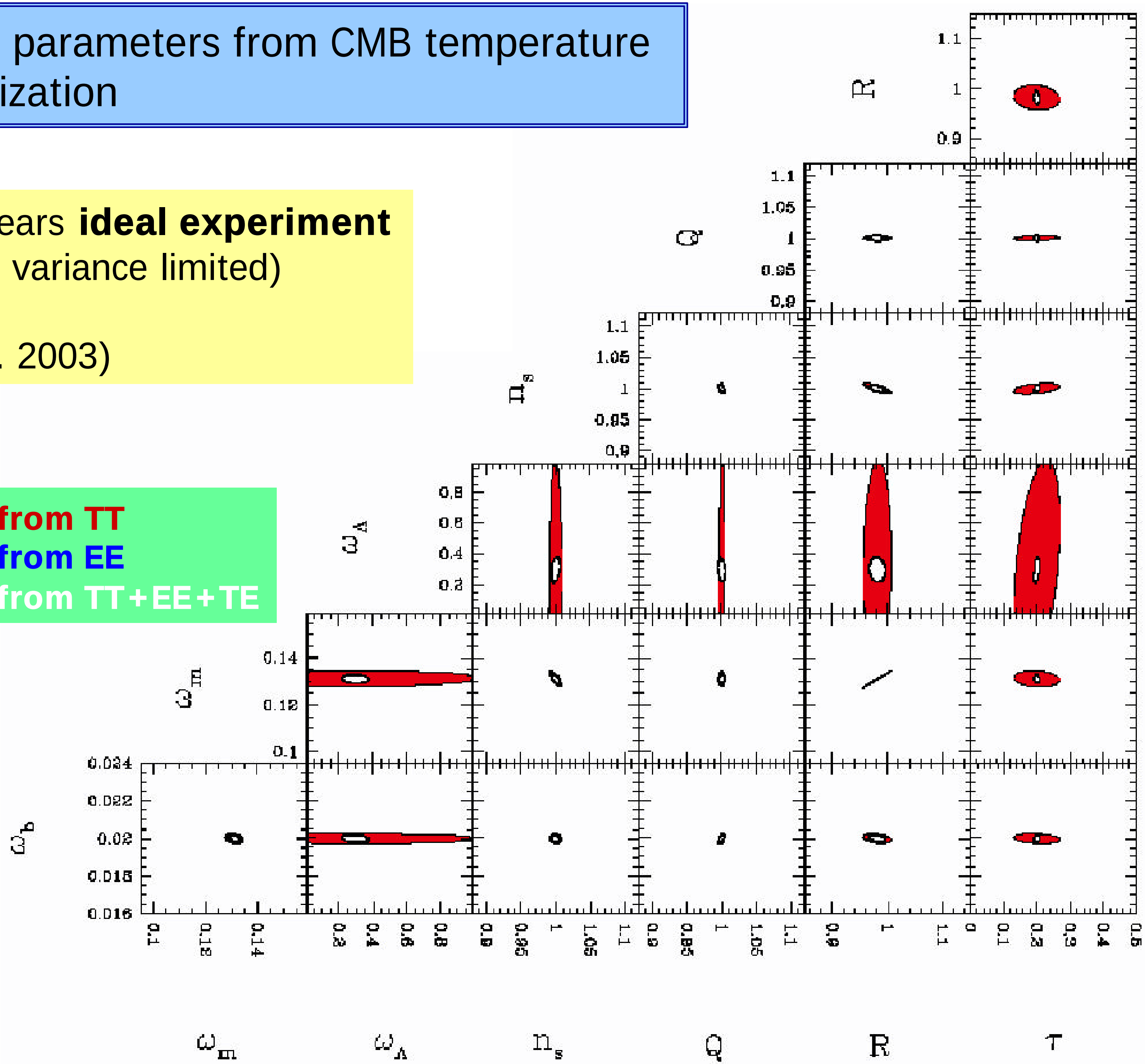
Constraints from TT
Constraints from EE
Constraints from TT+EE+TE



Cosmological parameters from CMB temperature and polarization

Forecast 2 years **ideal experiment**
(only cosmic variance limited)
2σ contours
(Rocha et al. 2003)

Constraints from TT
Constraints from EE
Constraints from TT+EE+TE

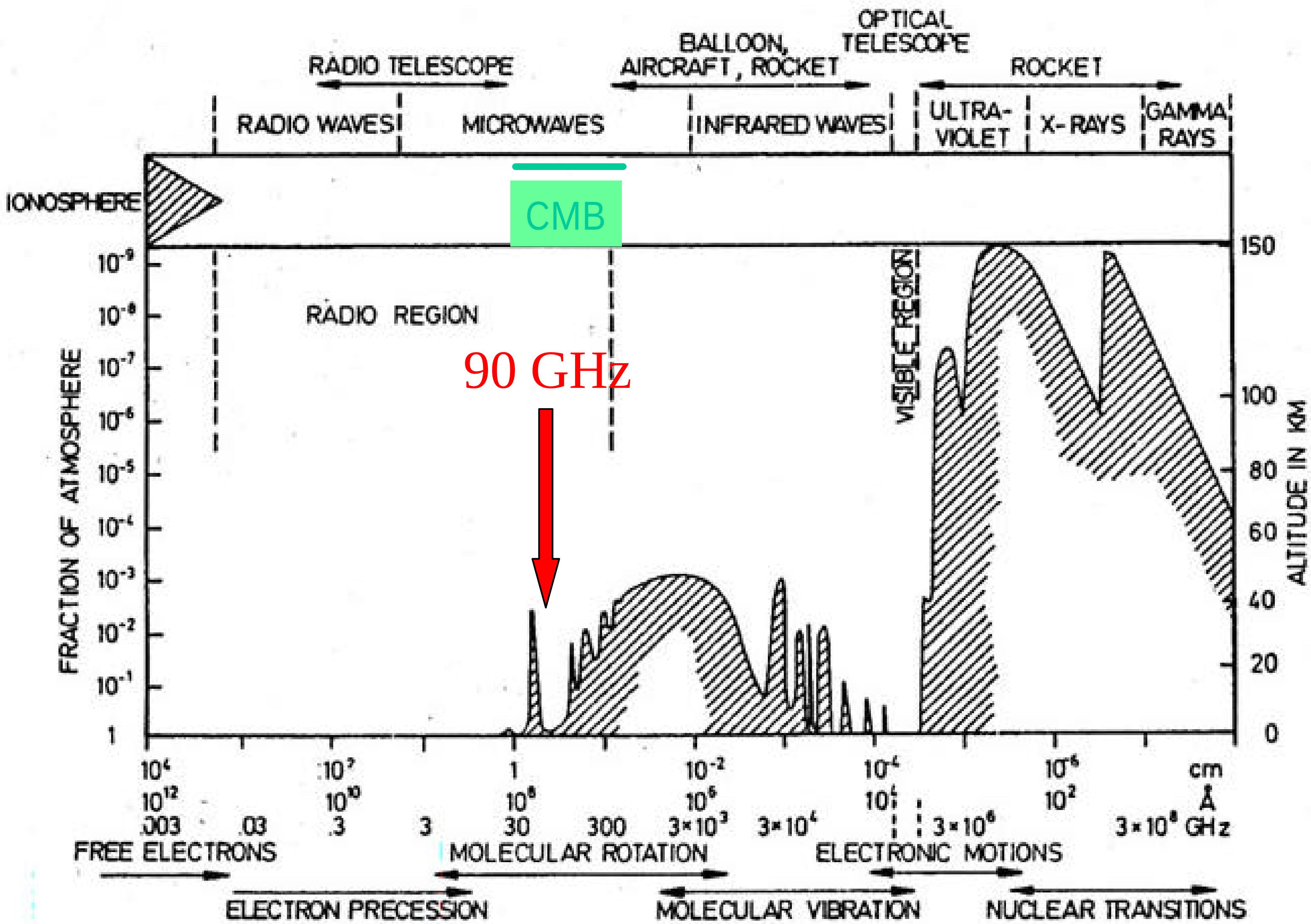


From the ideal to the real experiment

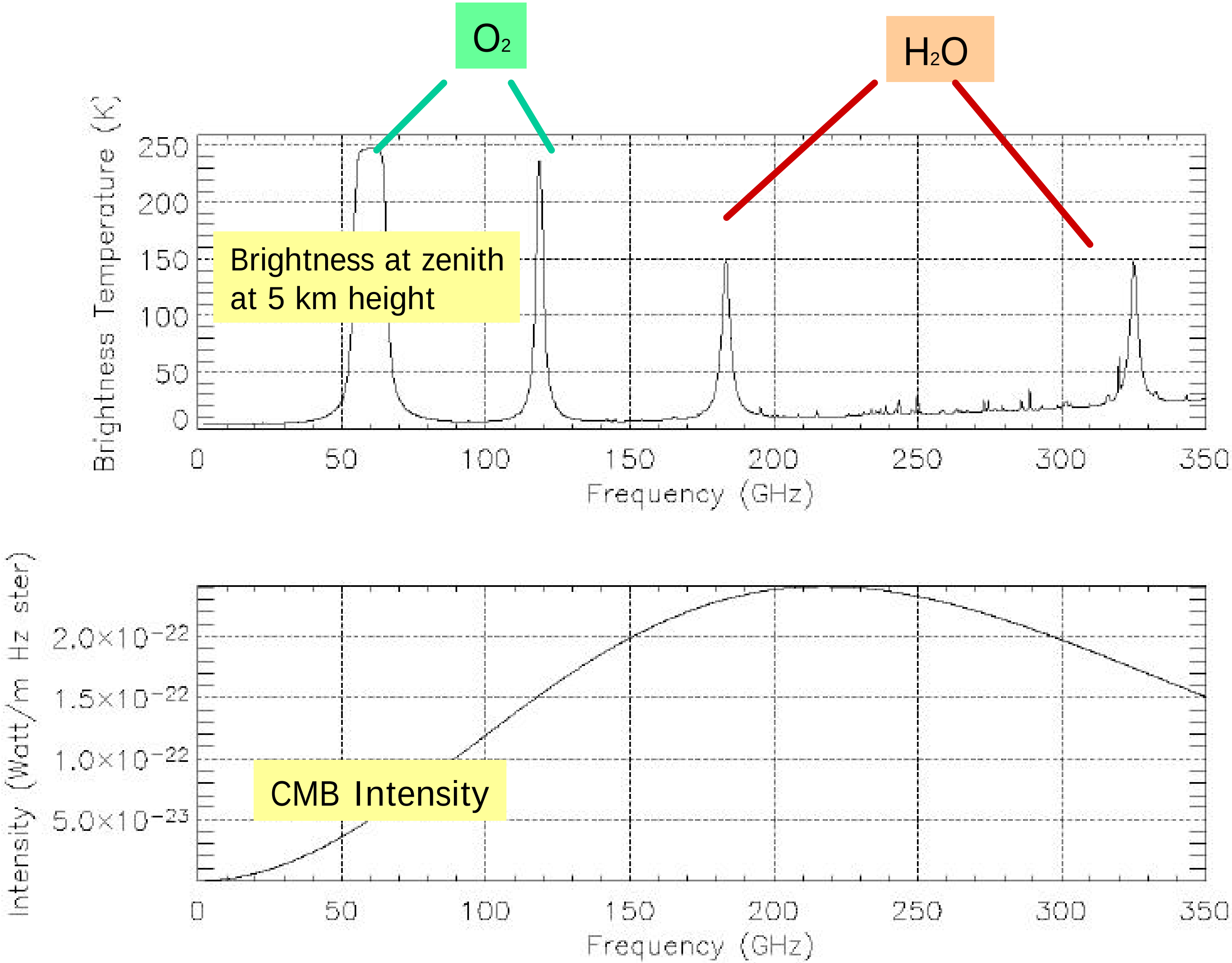
Choices for a CMB experiment

- Based at ground, balloon, space?
  effects of atmosphere, field of view

Atmospheric opacity



Atmospheric opacity



Choices for a CMB experiment

- Based at ground, balloon, space?
  effects of atmosphere, field of view
- Which frequency to observe?
  effects of foregrounds

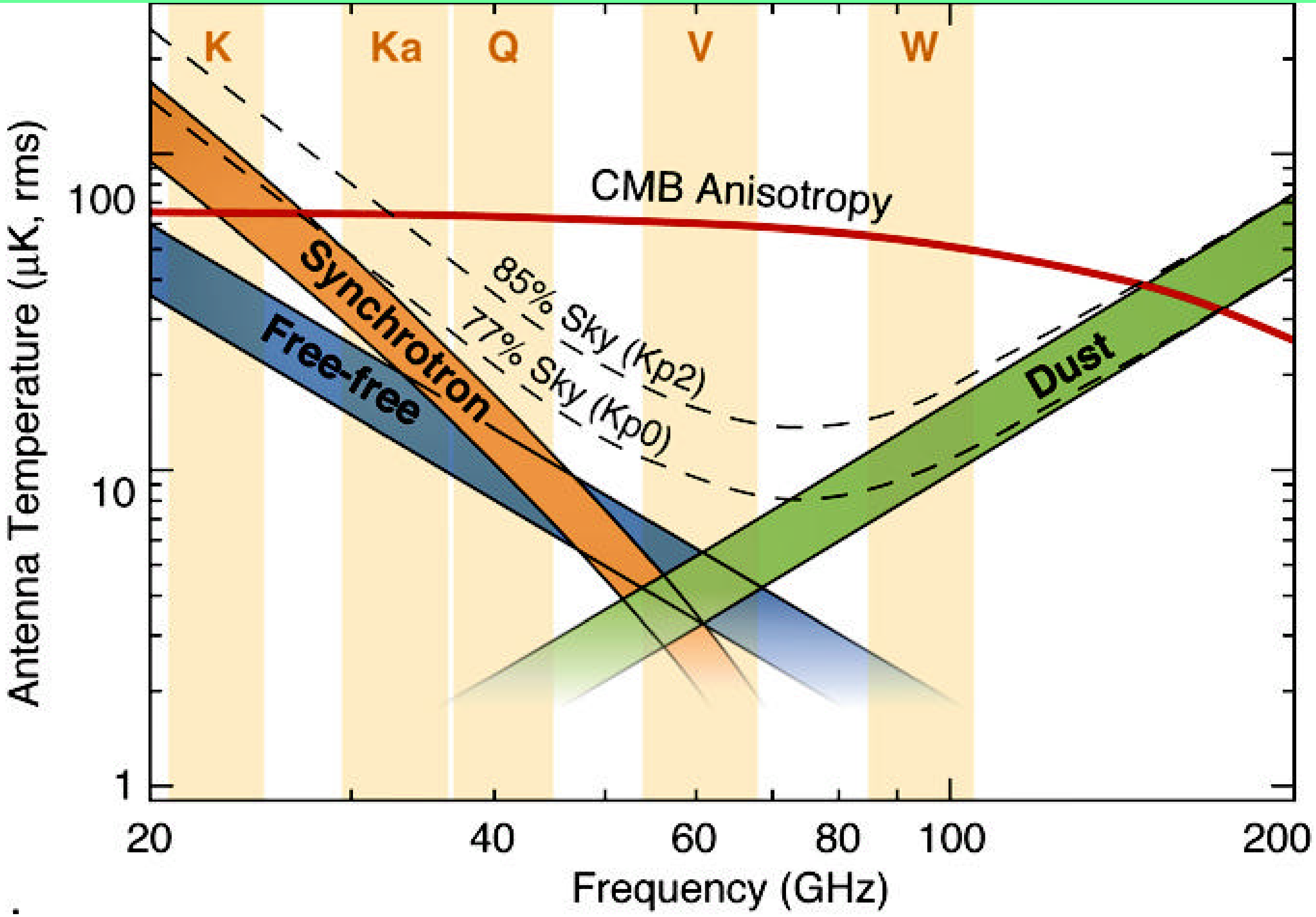
Astrophysical Foregrounds

Estimates by WMAP of the temperature RMS as a function of frequency
(extrapolation from maps at different frequencies)

Level of polarization not well determined with measurements, **dependent on scan region.**

Best estimates for average fraction of intensity:

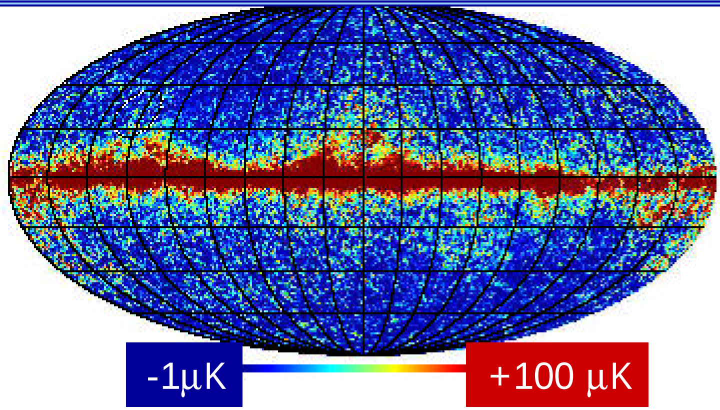
Synchrotron: 10-75%
Free-free: <10%
Dust: <10%



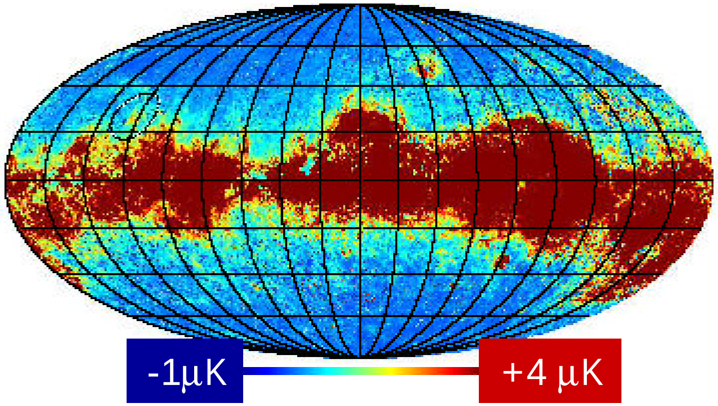
Graph by WMAP *http://lambda.gsfc.nasa.gov/product/*

WMAP 94 GHz derived temperature maps

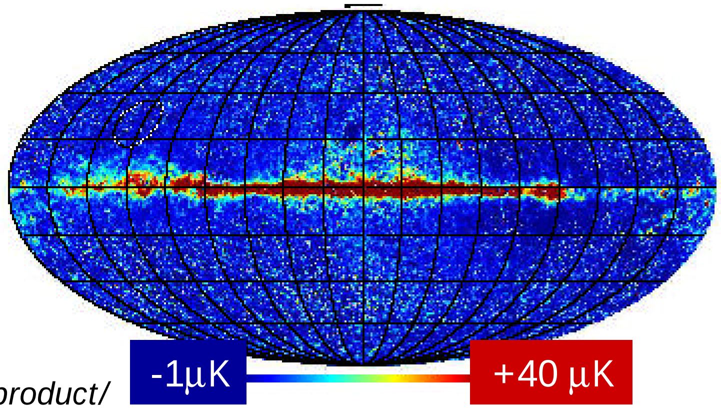
synchrotron



free-free



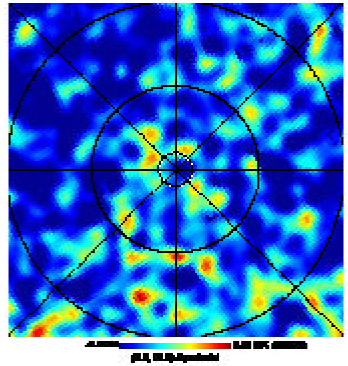
dust

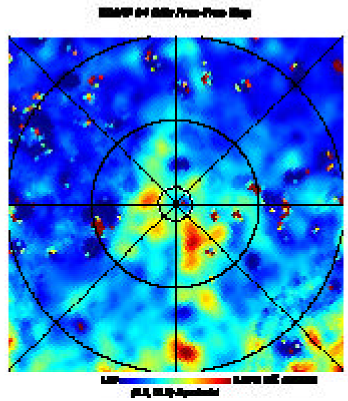


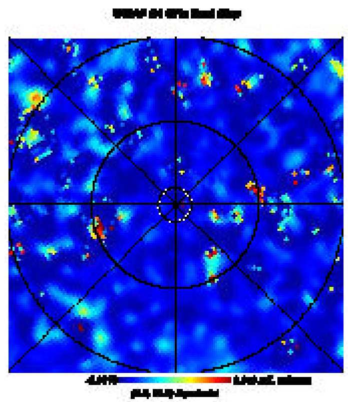
Graphs by WMAP
http://lambda.gsfc.nasa.gov/product/

North Celestial Pole

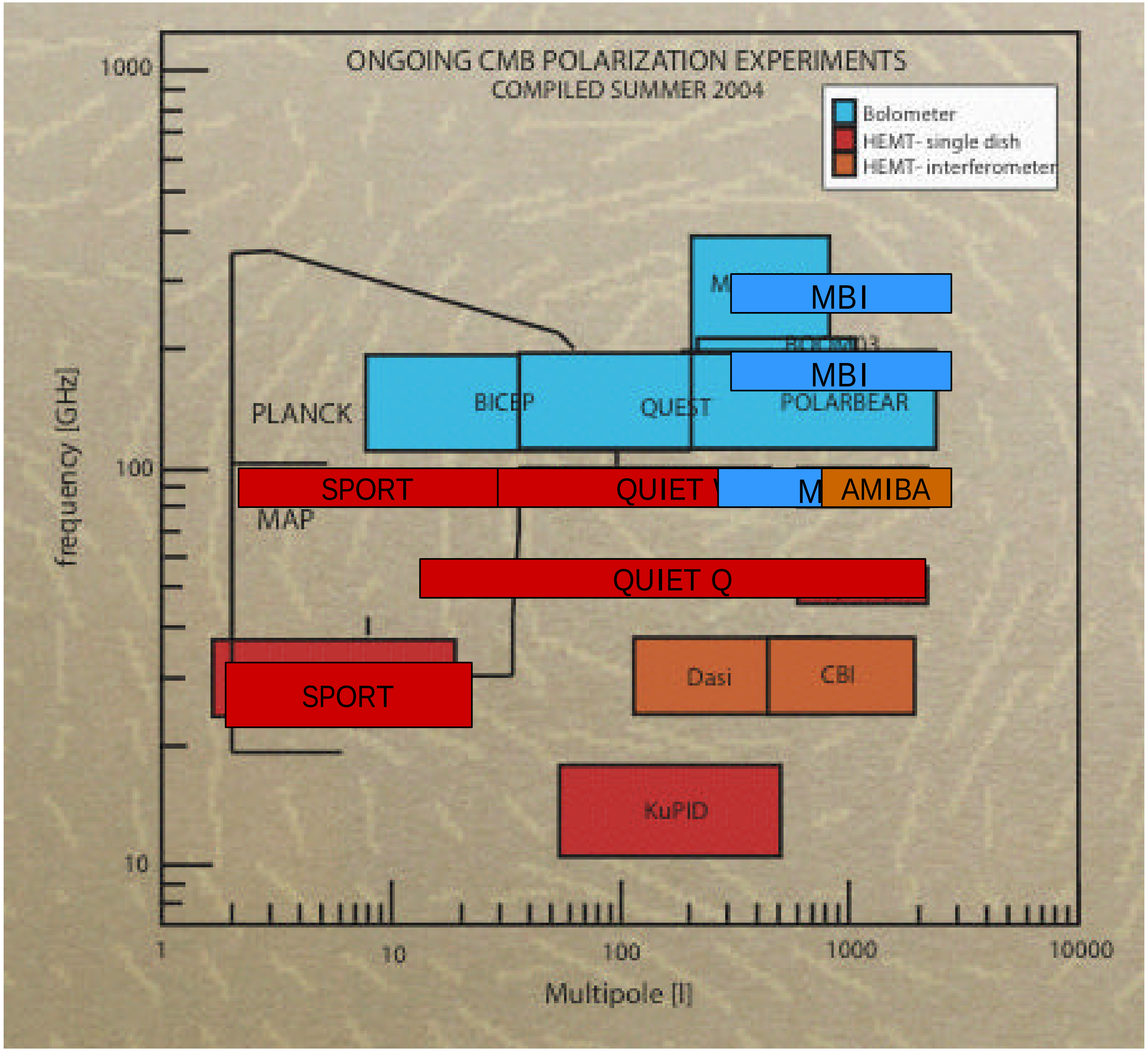
(CAPMAP scan region)







Ongoing CMB polarization experiments



Choices for a CMB experiment

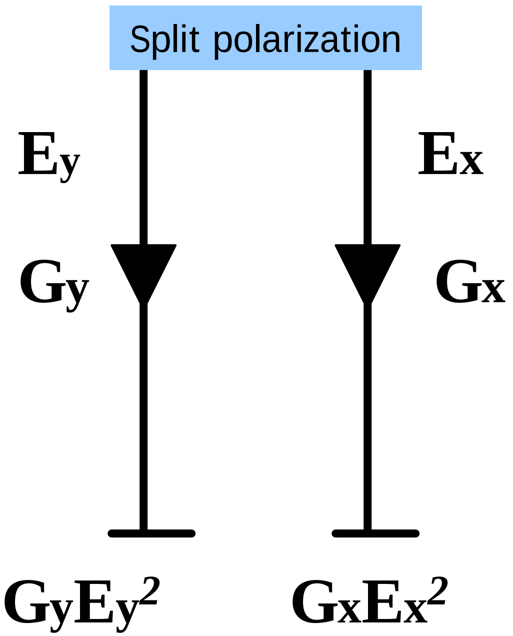
- Based at ground, balloon, space?
  effects of atmosphere, field of view

- Which frequency to observe?
  effects of foregrounds

- Which techniques to apply?
  (HEMT/Bolometers, large/small dish)
  large sensitivity, little noise and systematics, sufficient angular resolution

Experimental techniques

Differencing polarimeters

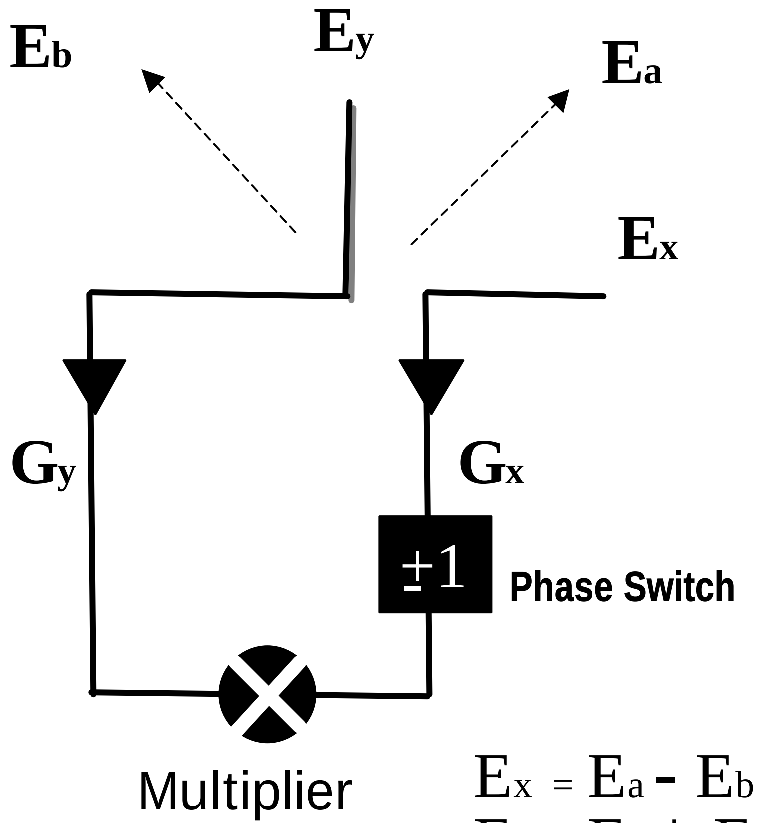


Description of polarization patterns in Stokes parameters Q and U:

$$Q = \langle E_y^2 \rangle - \langle E_x^2 \rangle$$

$$U = \langle E_a^2 \rangle - \langle E_b^2 \rangle$$

Correlation polarimeters



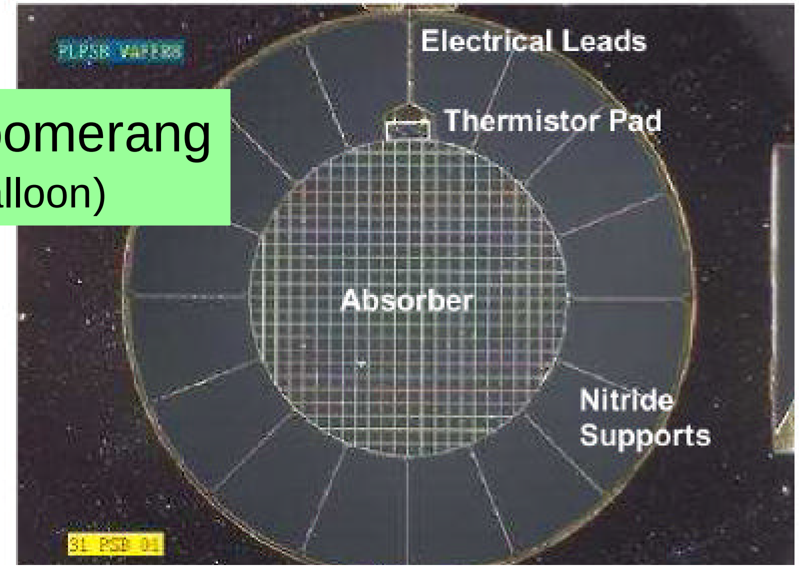
$$E_x = E_a - E_b$$

$$E_y = E_a + E_b$$

$$\text{Output} = G_x G_y (E_x E_y) = \pm G_x G_y (E_a^2 - E_b^2)$$

CMB polarization experiments (using bolometers)

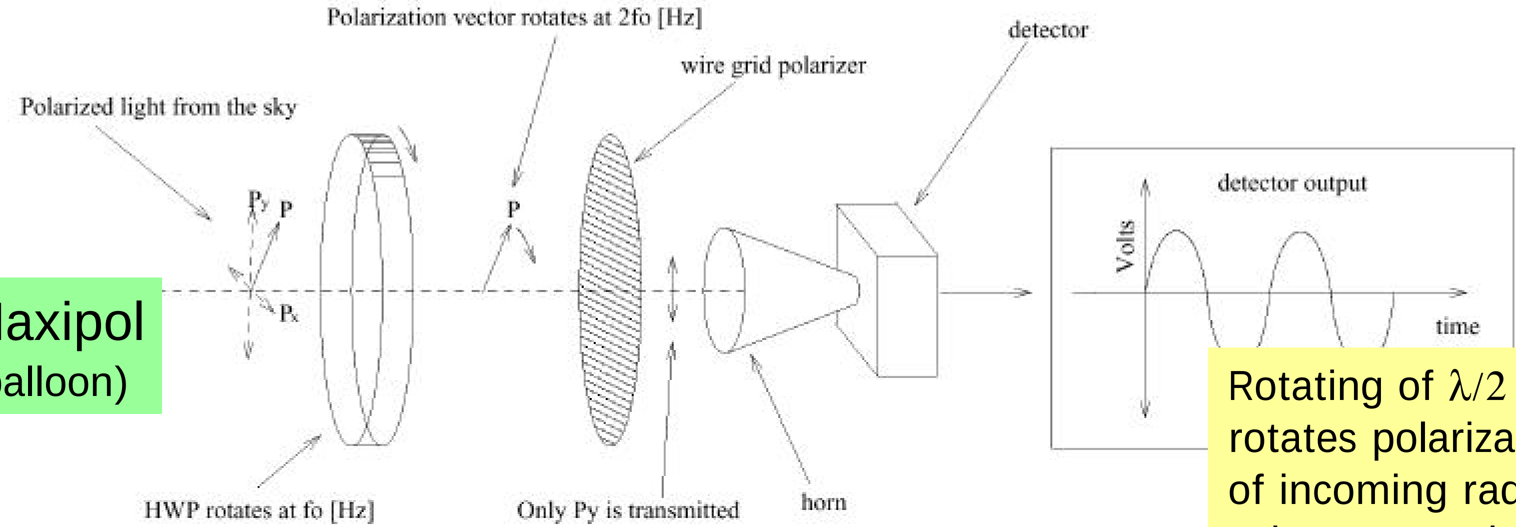
Boomerang
(balloon)



Polarization **S**ensitive **B**olometer (PSB)
Metallization of grid makes it sensitive to only one polarization direction

also in use in Planck (satellite)

Maxipol
(balloon)



Rotating of $\lambda/2$ plate rotates polarization vector of incoming radiation, subsequent wire grid filters one polarization direction

CAPMAP experiment

Collaboration of Princeton, Chicago, Miami, JPL

- Observing Site: Crawford Hill, NJ
- Telescope: 7-meter Off-axis Cassegrain
- Scan Strategy: Azimuth Scan on 1° cap at NCP
- Receivers: 16 Heterodyne Correlation Polarimeters

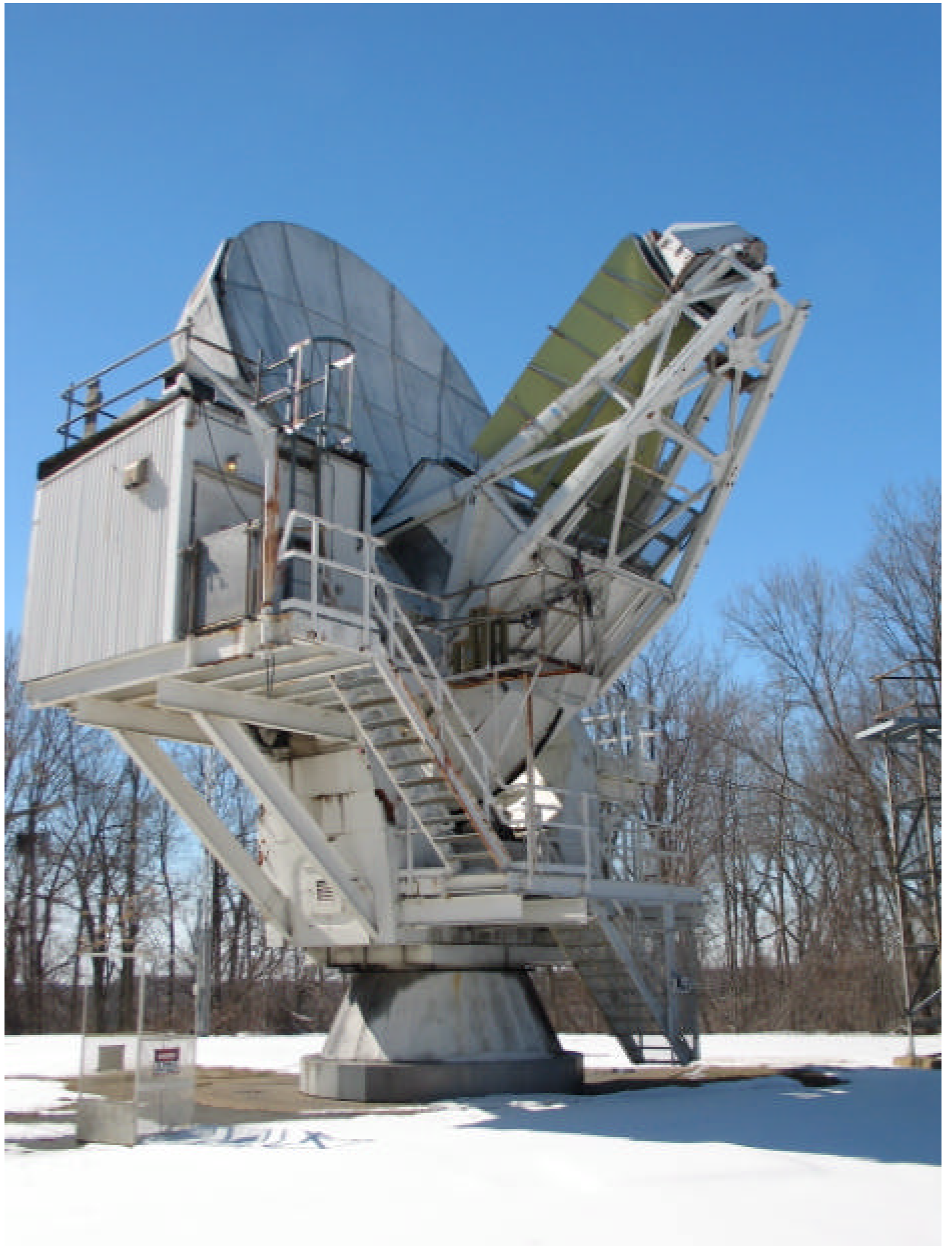
  12 W-Band (84-100 GHz)

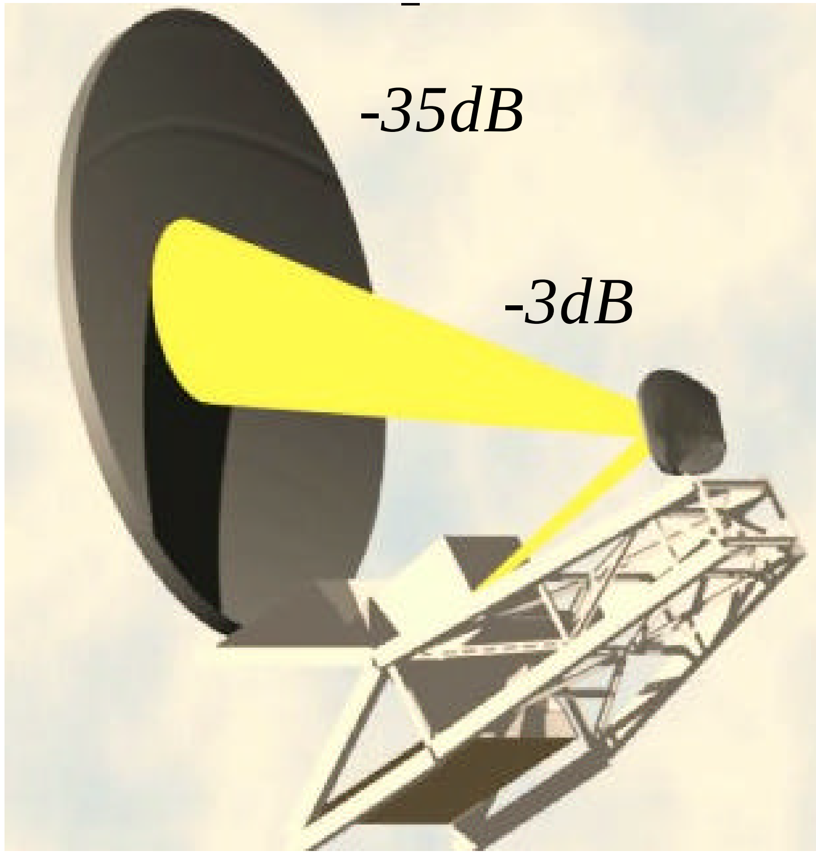
  4 Q-Band (35-45 GHz)

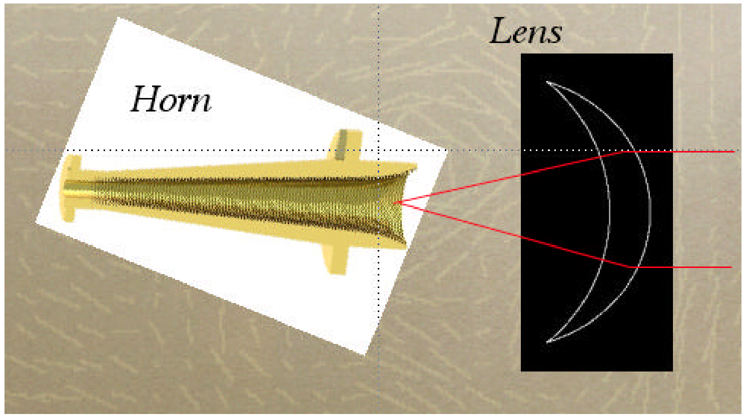
	W-band	**Q-band**
FWHM	4' (0.06°)	6' (0.1°)
Receiver Noise Temperature	60 K	25 K
Sky Noise Temperature	40 K	10 K
Bandwidth	12 GHz	8 GHz
Sensitivity/Receiver	1 mK $s^{1/2}$	400 μK $s^{1/2}$

Optics

Avoid spillover to minimize
pickup from ground, trees, and ...

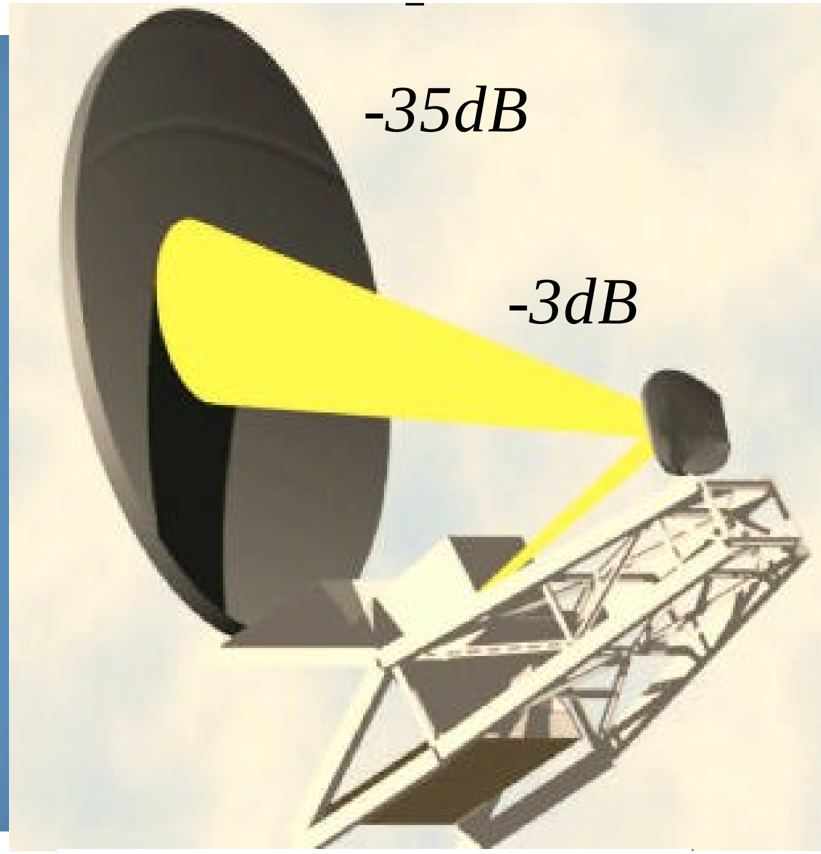


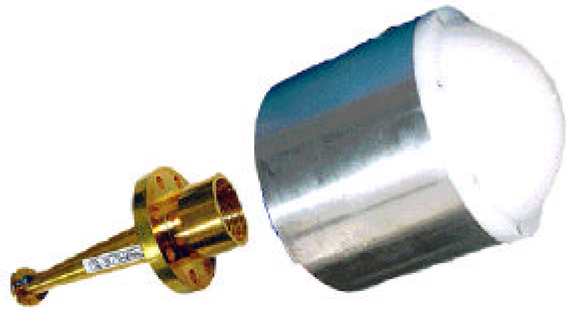




Optics

Avoid spillover to minimize pickup from ground, trees, and ...





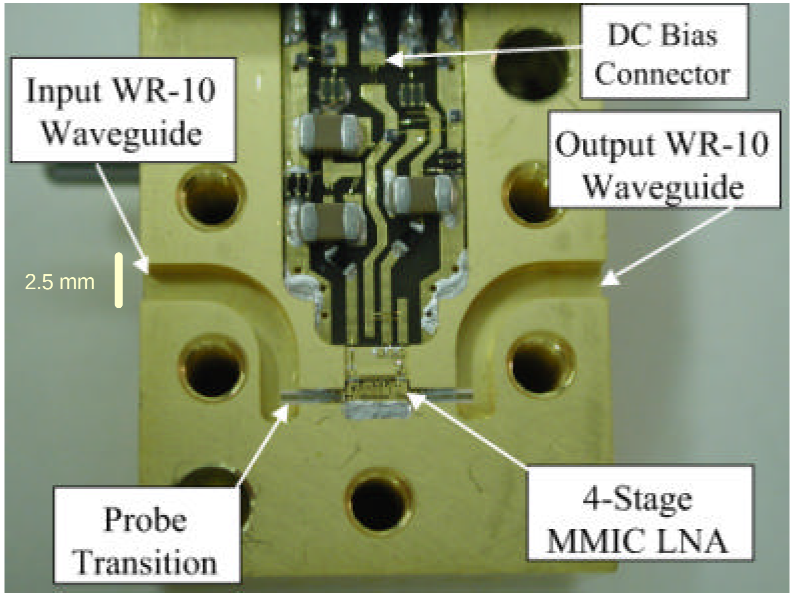
Amplification by MMIC HEMTs

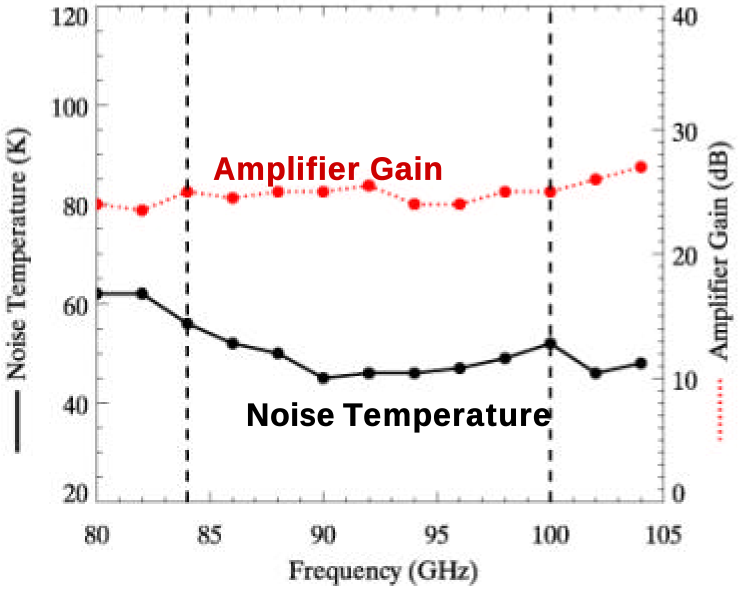
MMIC HEMT

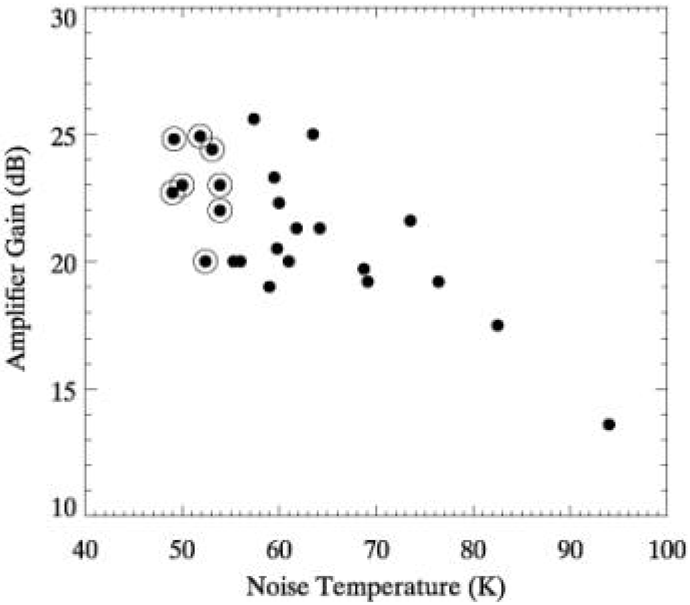
***M**onolithic **M**icrowave **I**ntegrated **C**ircuit*

***Hi**gh **El**ectron **M**obility **T**ransistor*

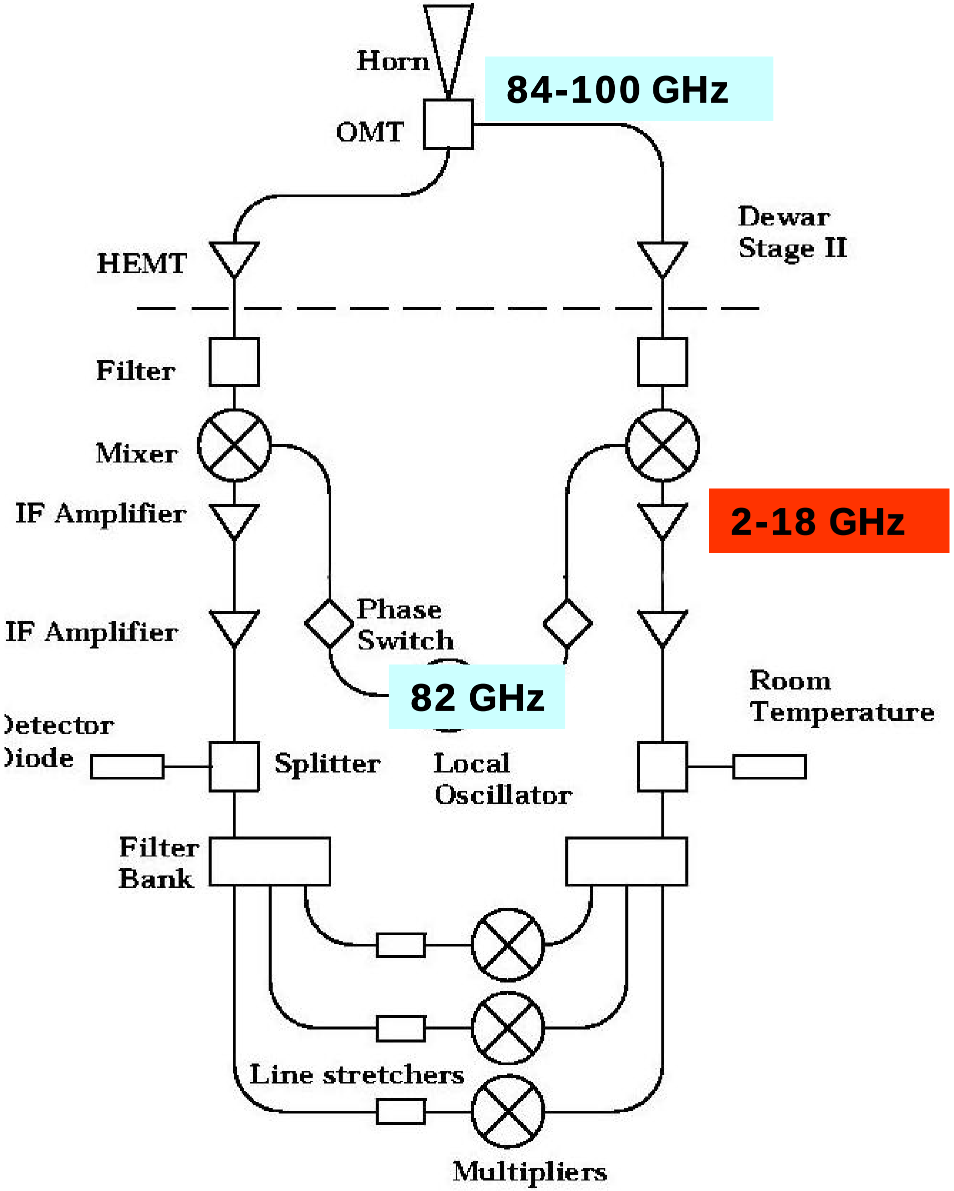
- low noise (~50 K)
- high gain (~22 dB)
- high bandwidth (~16 GHz)
- small
- cooled to 20K

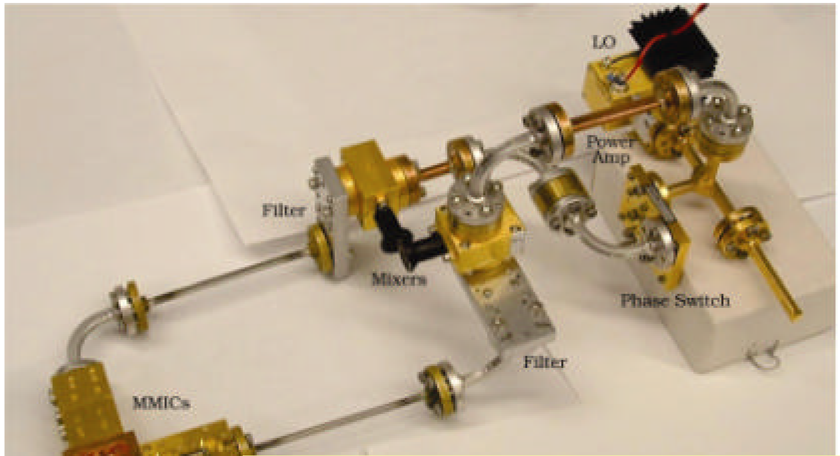




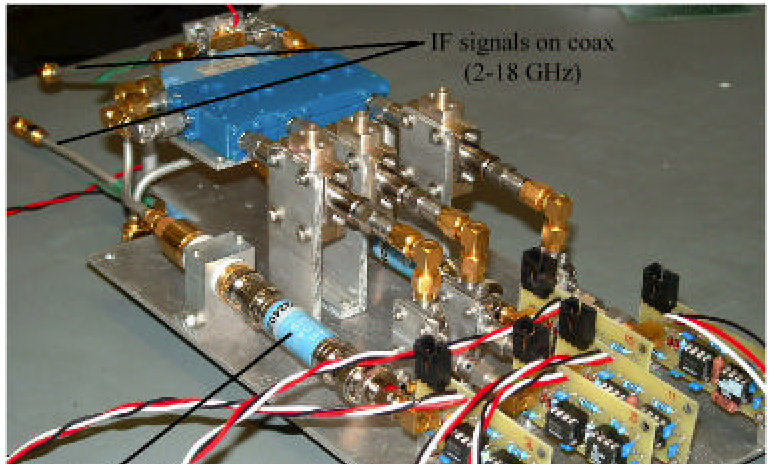


CAPMAP Correlation Polarimeter



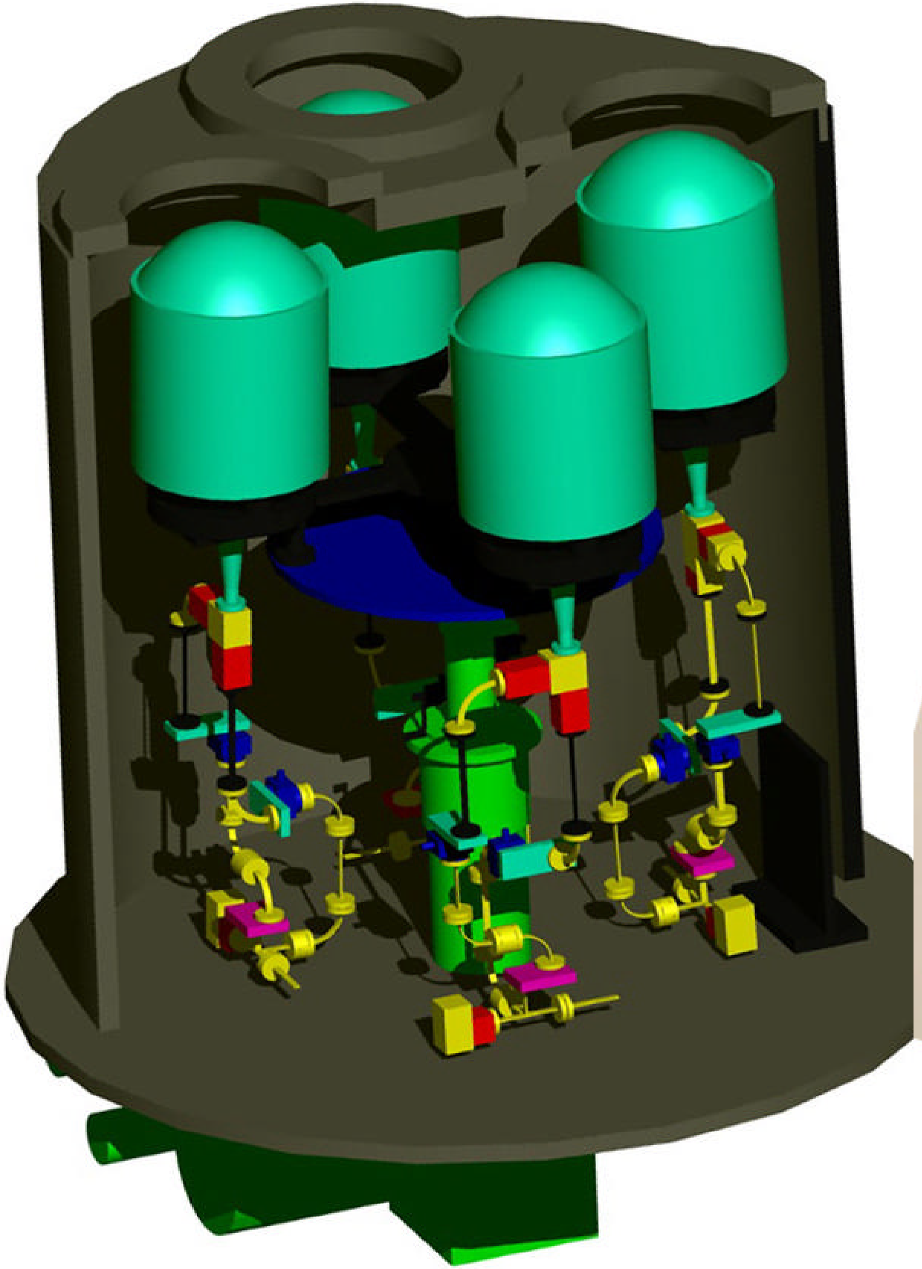


Radio frequency signal in waveguides (84-100 GHz)

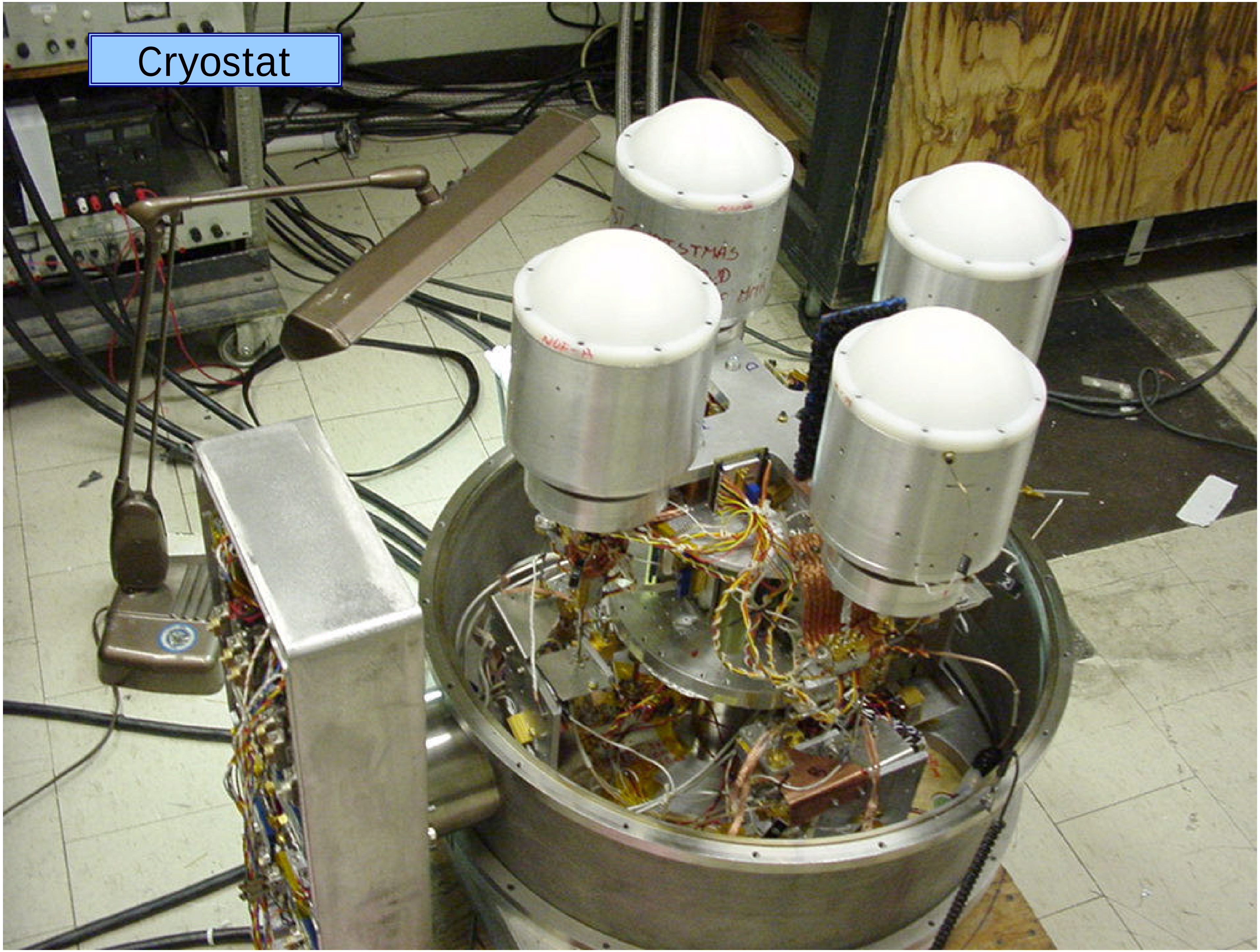


Intermediate frequency signal on coax (2-18 GHz)

Cryostat

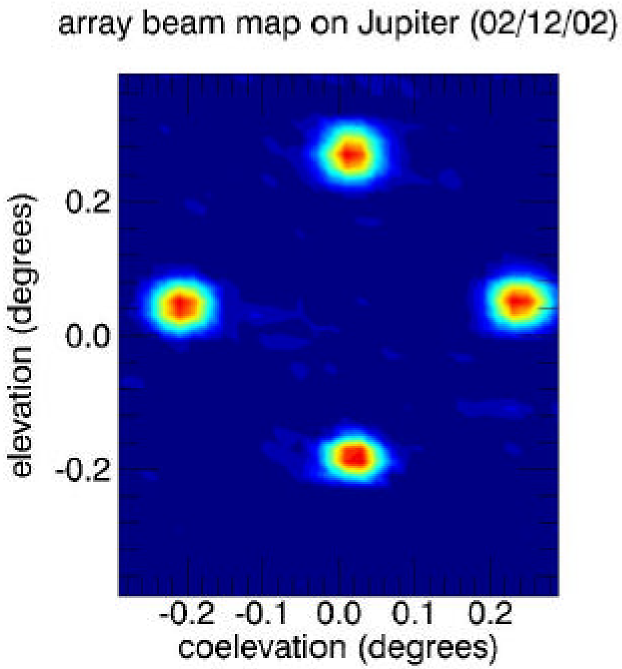


Cryostat



Calibration

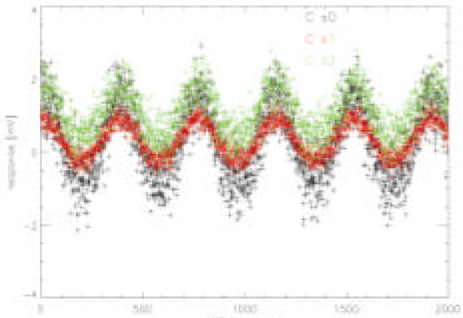
Total power channels



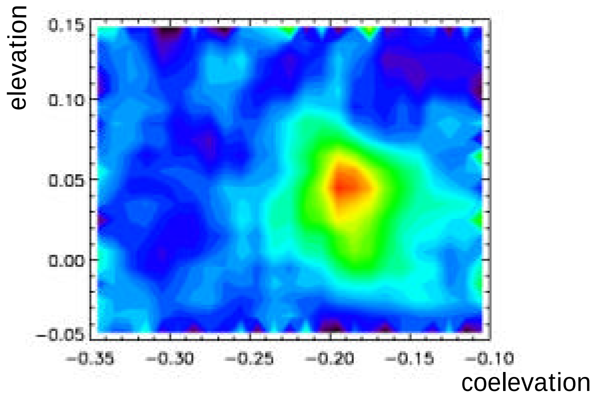
Jupiter scans and elevation scans
(20-90 elevation with constant azimuth)

Uncertainty in beamsize <2%
Uncertainty in pointing ~1/8 beam size

Polarimeter channels



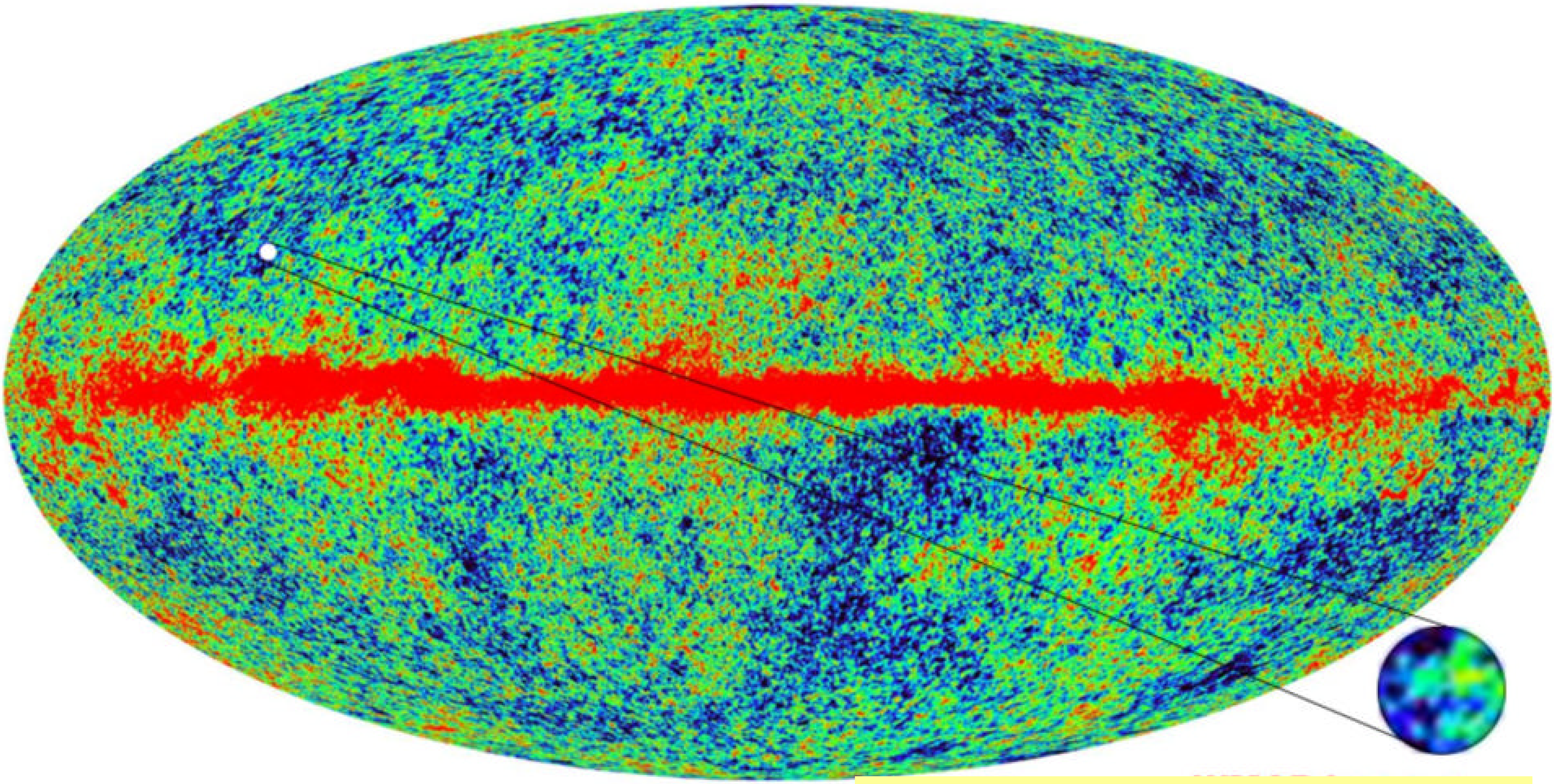
nutating chopper plate in front of secondary mirror



Cross checked with Taurus A
(Crab Nebula)

Overall calibration uncertainty ~10%
Relative uncertainty ~3%

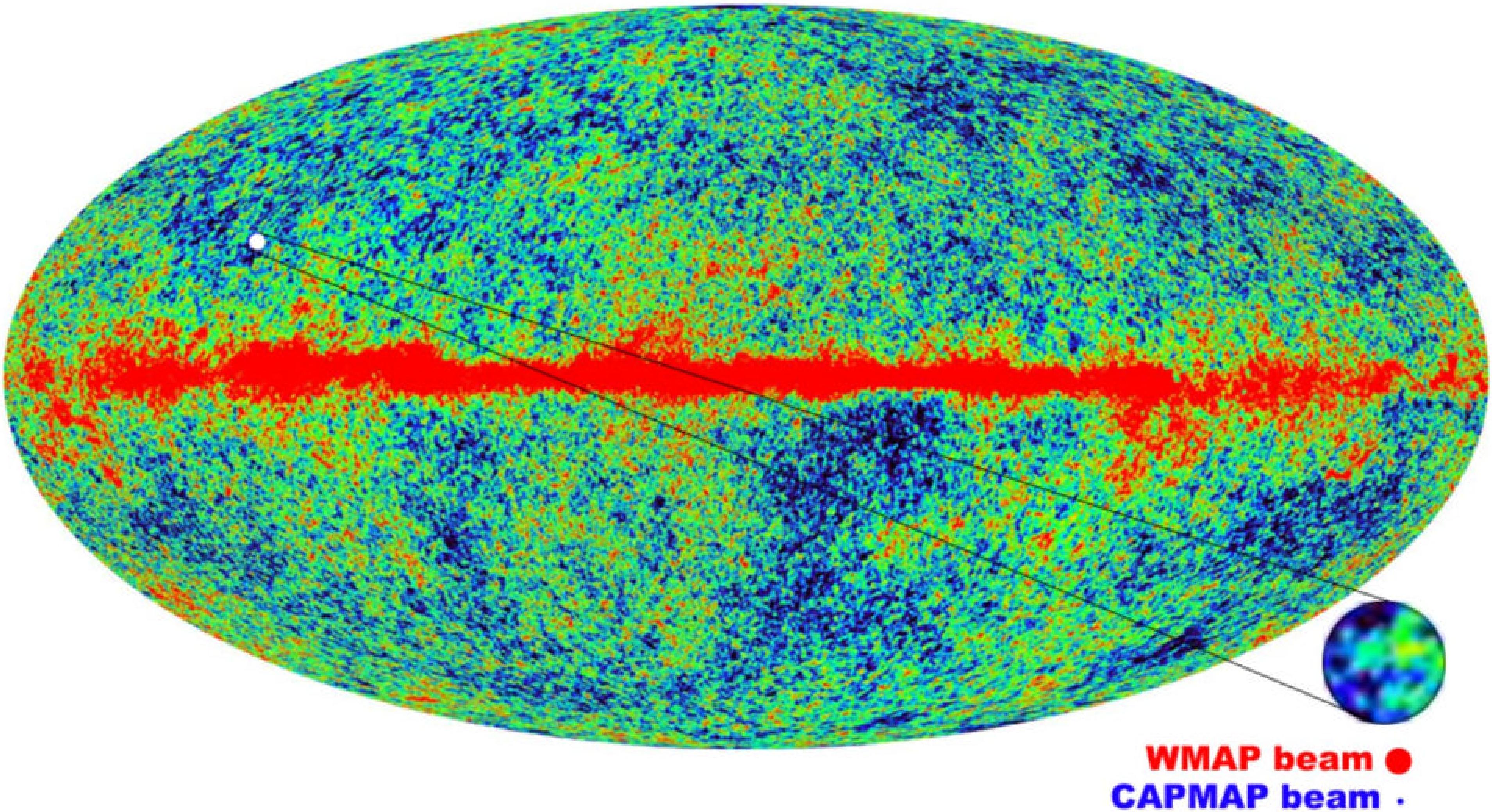
CAPMAP scan region



1 degree cap around **N**orth **C**elestial **P**ole

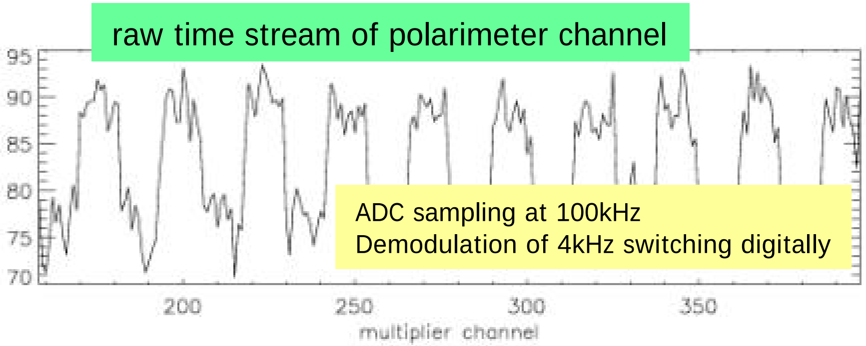
Scanning azimuthally at constant elevation, sky is rotating beneath

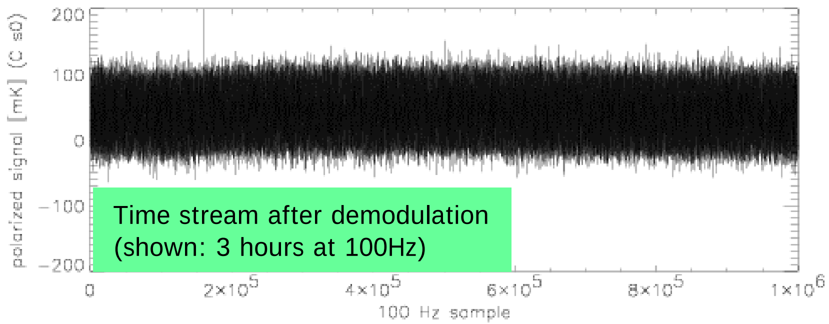
CAPMAP scan region

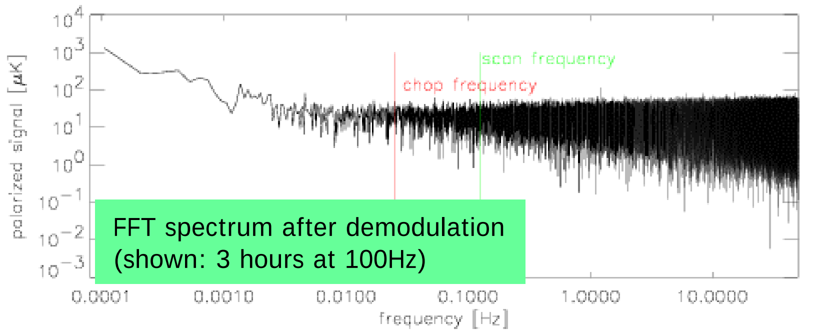


Scanning azimuthally at constant elevation, sky is rotating beneath

Real data



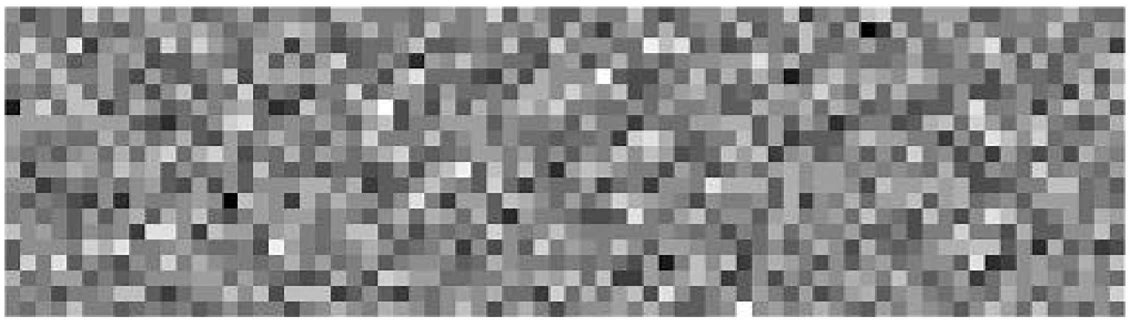




- Select good data (weather), remaining 430 hours
- Subtract scan synchronous structures
- Form data vectors (azimuth x LST)
- Coadd data vectors for different frequencies

Data vector for receiver C

20 bins (azimuth)



72 bins (Local Sidereal Time)

Greyscale: –210-210 μK

Maximum likelihood analysis

$$P(d\,|\,C_T) \propto \frac{1}{\sqrt{\det(C)}} \exp(-\frac{1}{2} d^T C^{-1} d)$$

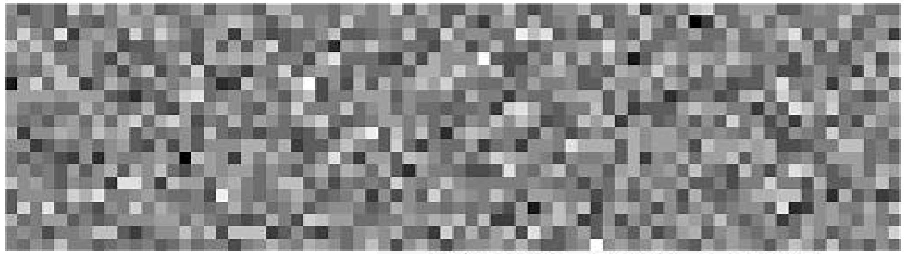
d : Data vector

C = C_N + C_T

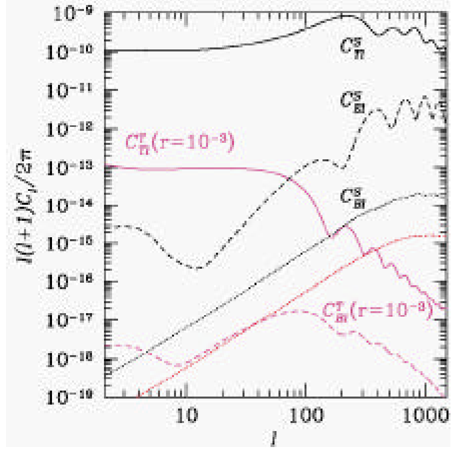
C_N : Noise covariance

C_T : Theory covariance

C is for CAPMAP 5760x5760 matrix



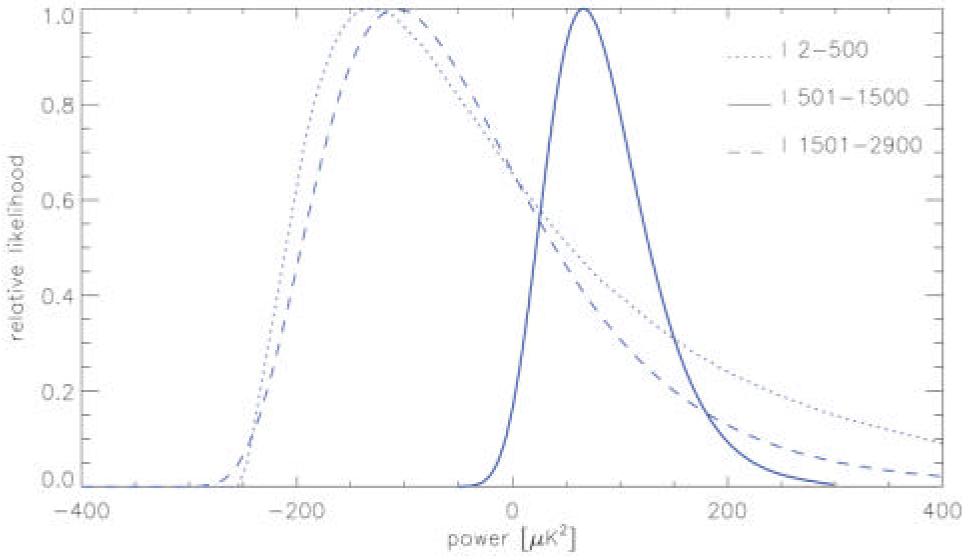
?



Projection onto subspace without degrees of freedom
which were eliminated by the offset removal

First results from CAPMAP

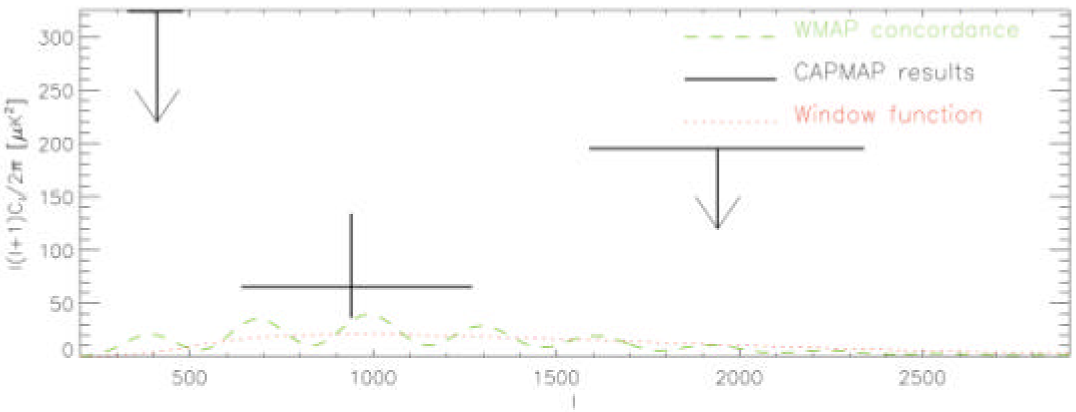
(first measurement of CMB polarization at 90 GHz)



Data from first season
(4 W-band receivers)

Likelihood curves
for 3 different l-ranges

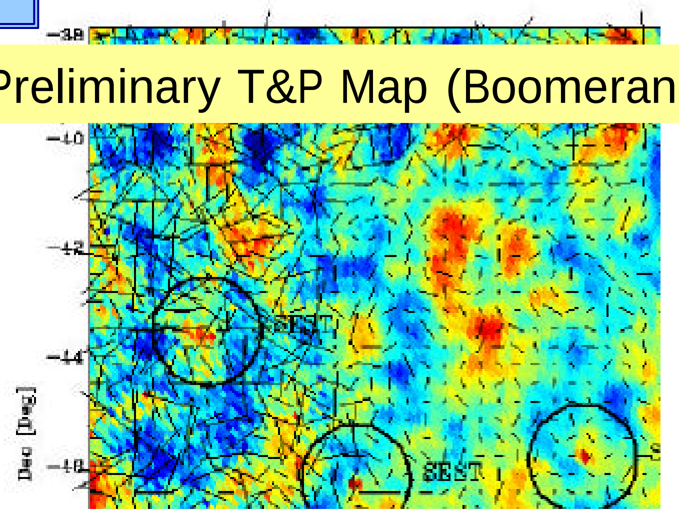
2σ 'detection' of polarization
in the middle band



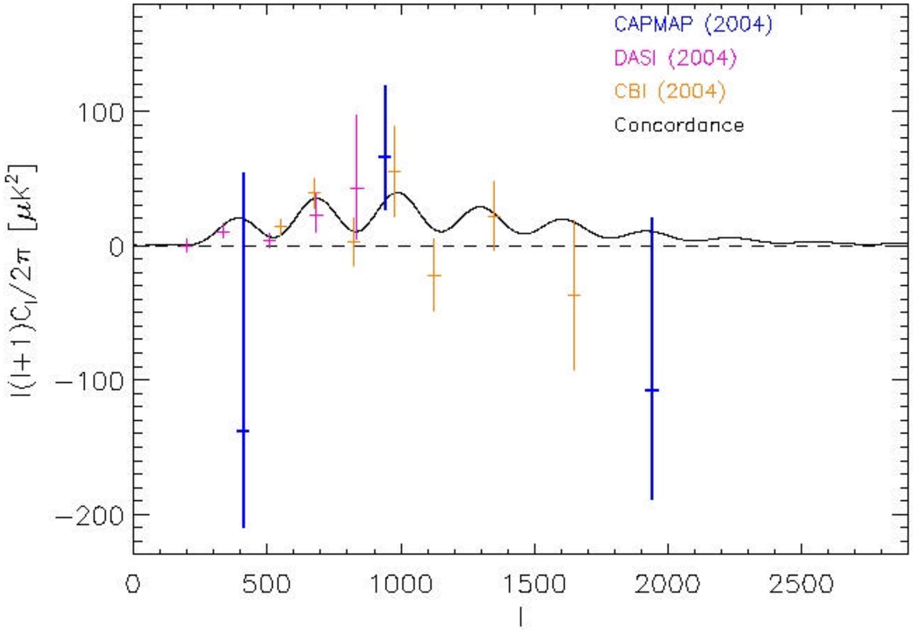
Status of Polarization measurements

- 2002 Detection of E-mode polarization by **DASI**
- 2003 Measurement of TE correlation by **WMAP**
- 2004 Refined measurements of E-mode spectrum and TE correlation by **DASI, CBI, CAPMAP**

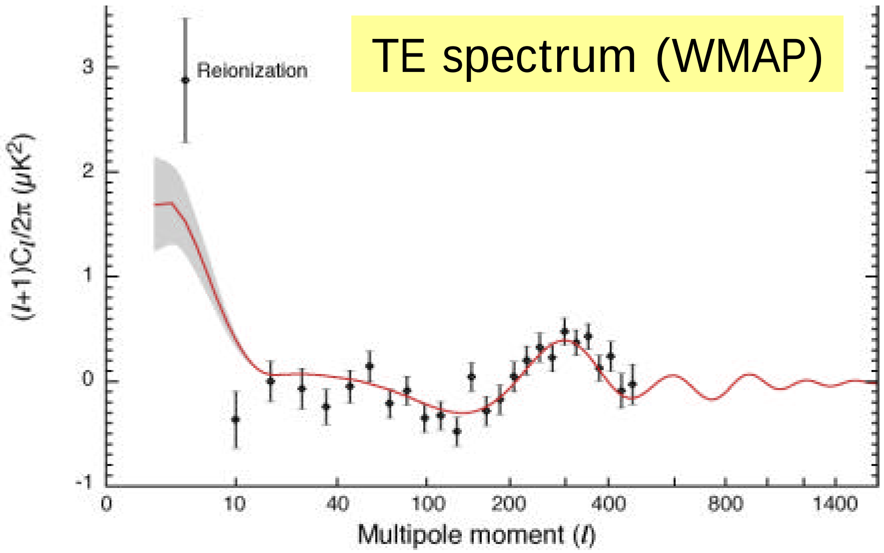
Preliminary T&P Map (Boomerang)



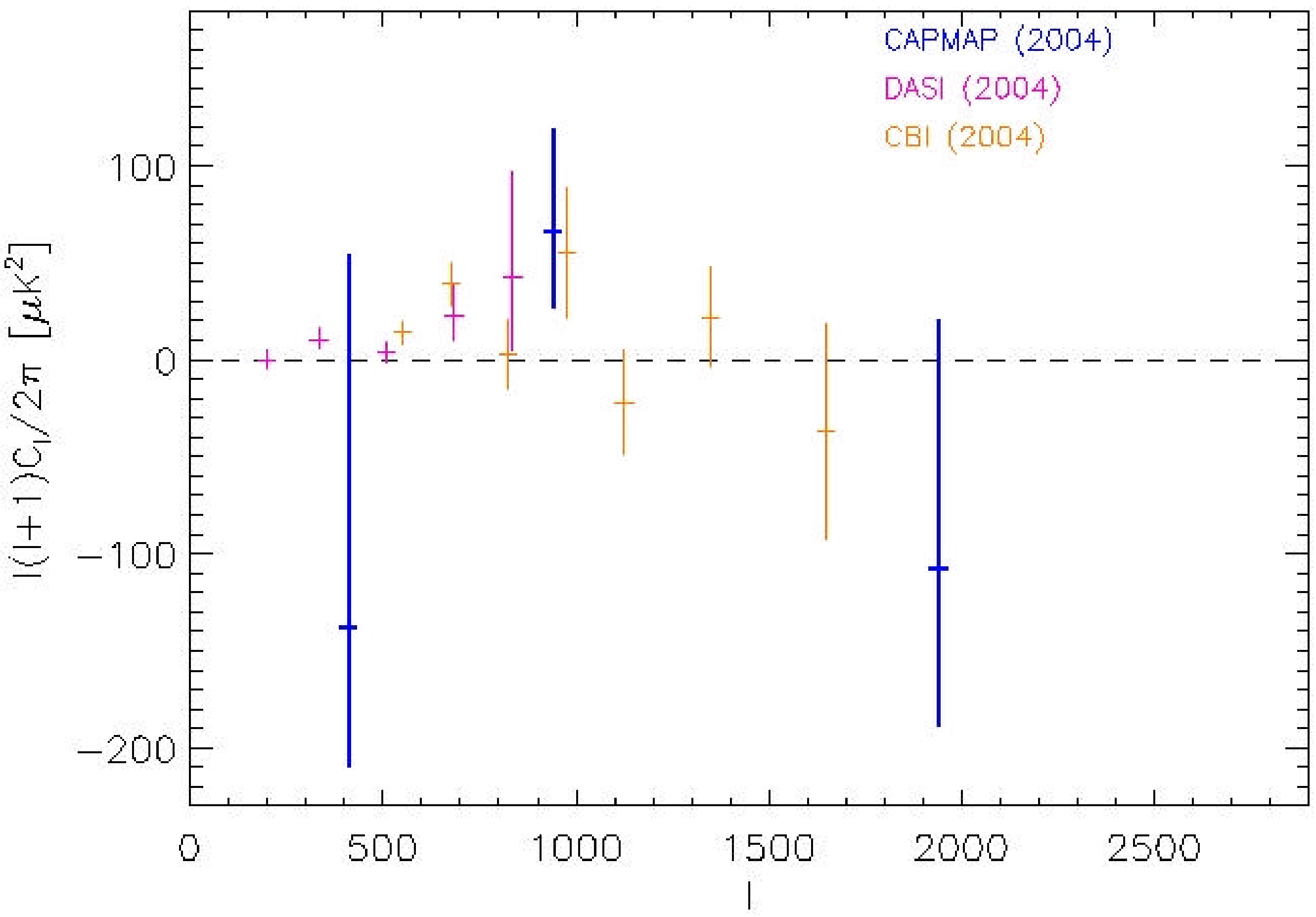
EE spectrum (DASI, CBI, CAPMAP)



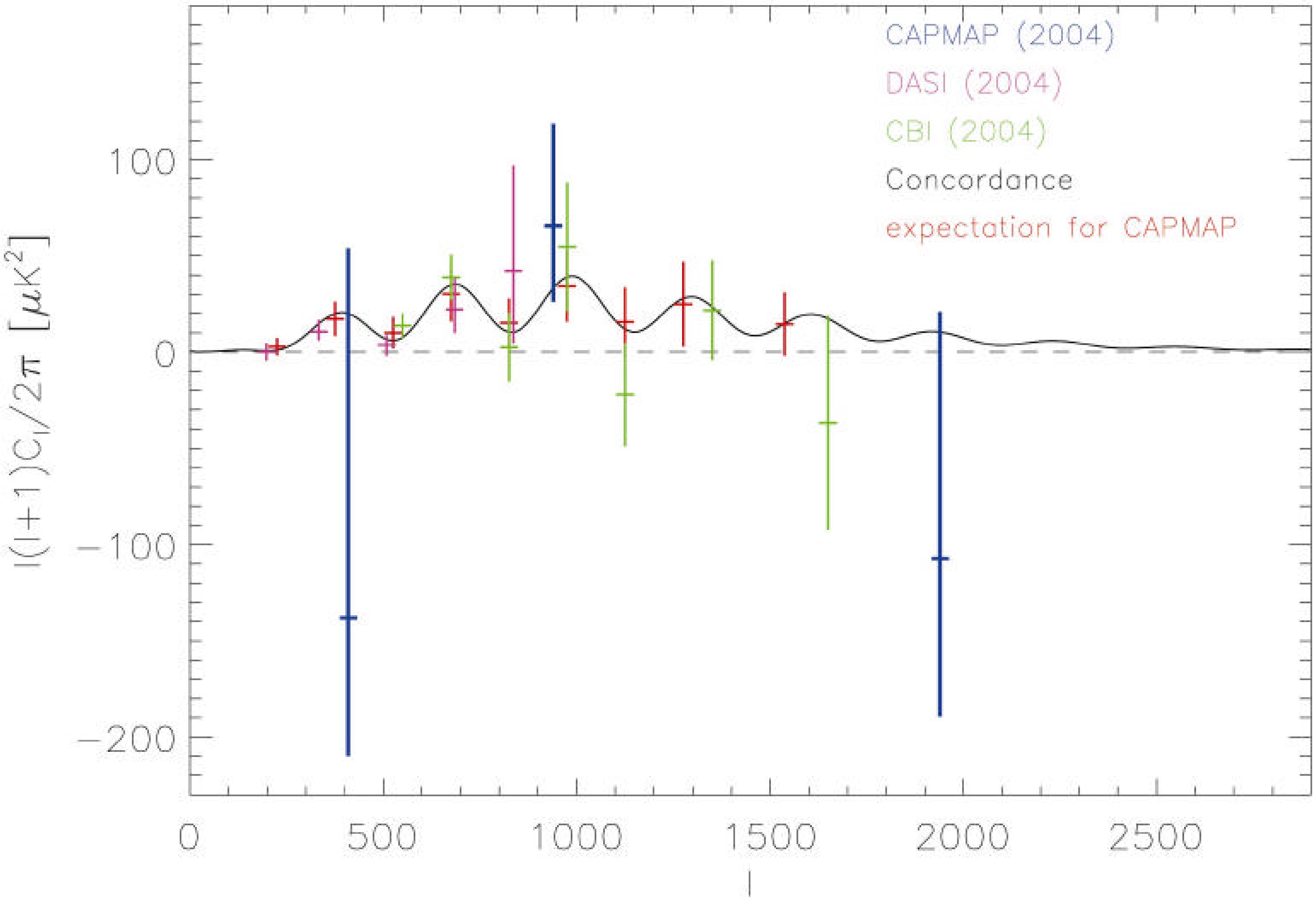
TE spectrum (WMAP)



Status of E-mode measurements



Expectation for CAPMAP



The future of CMB measurements

Goals:

- Precision E-mode spectrum

  (break parameter degeneracies)
- B-modes:

  - Lensing of the E-modes

    (neutrino mass)

  - Signature of primordial Gravity Waves

    (first insight to inflationary period, maybe link to GUT scale)

Challenges:

- High sensitivity needed

  (build large arrays)
- Excellent control of systematics

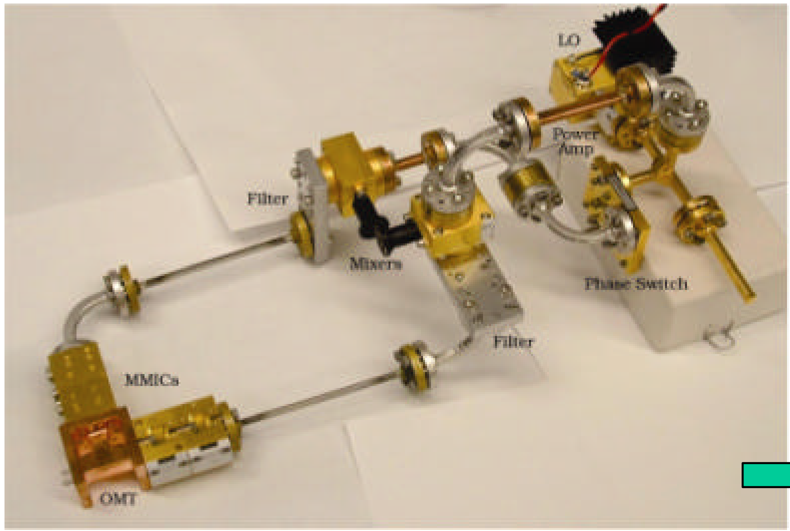
  (excellent control of instrumental and environmental 'features')
- Detailed understanding of foregrounds

  (choice of clean scan region, better measurements of the various foregrounds at different frequencies)

QUIET
Q/**U** **I**maging **E**xperimen**T**

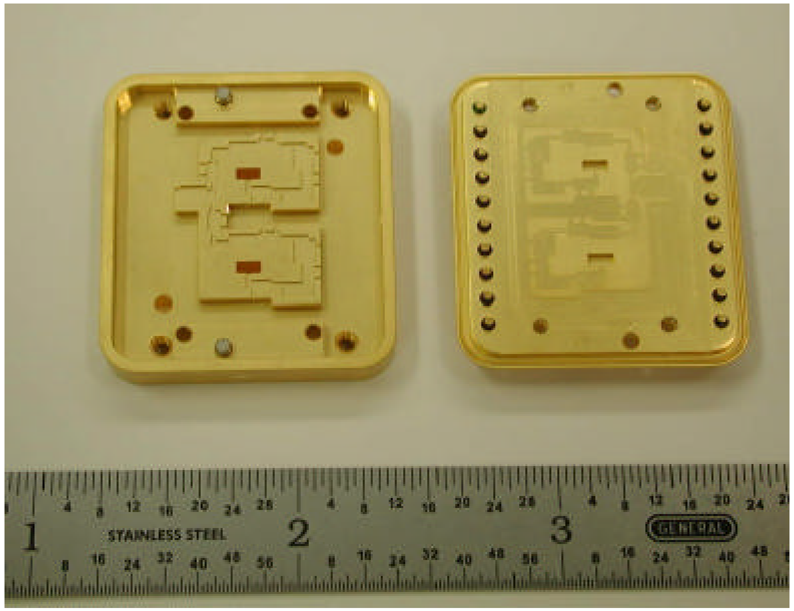
Collaboration by: Berkeley, Caltech, Chicago, Columbia, GSFC, Harvard Smithsonian, JPL, Miami, Princeton

- Large array of correlation polarimeters
- Fast, cost effective automated mass production of coherent polarimeters

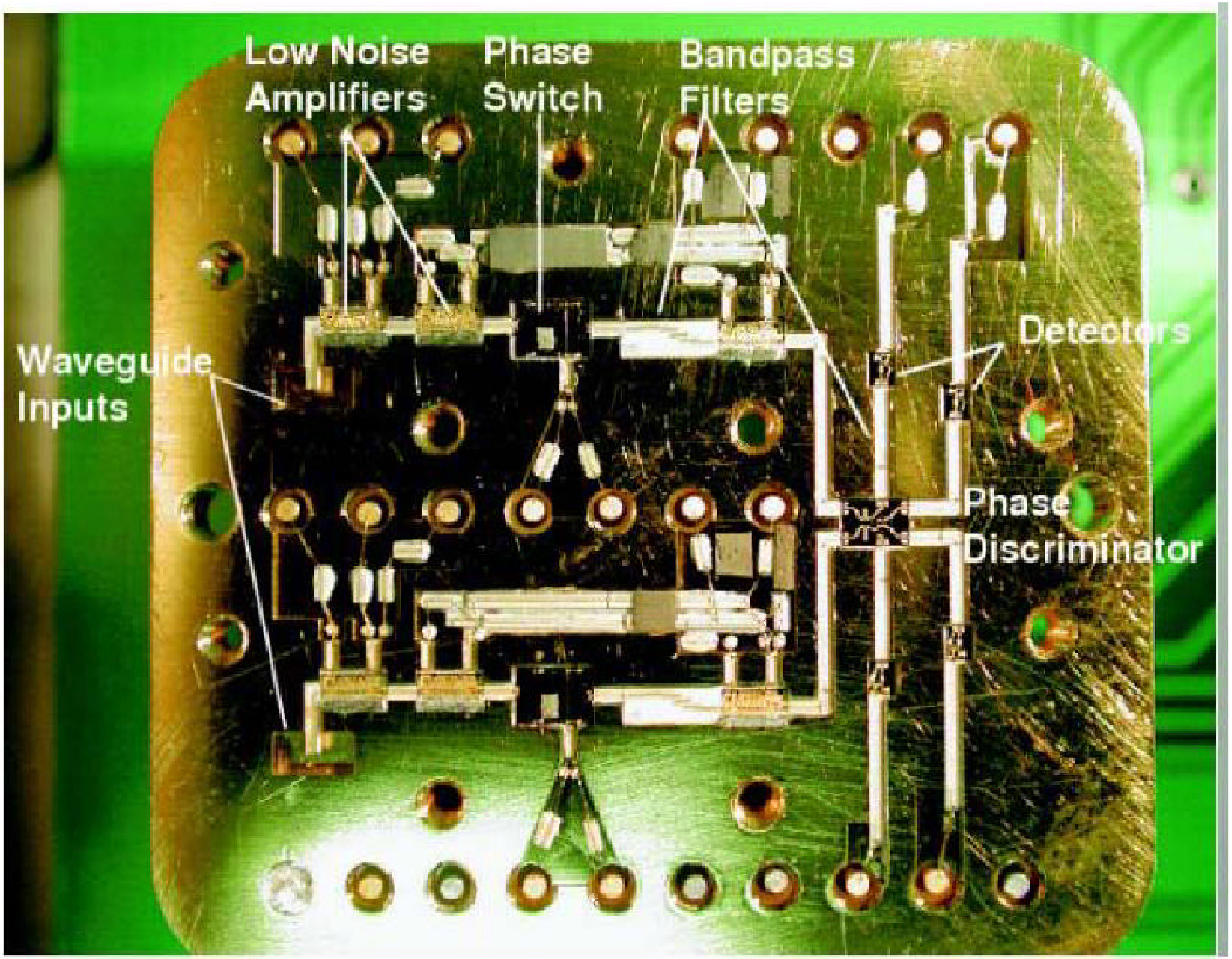


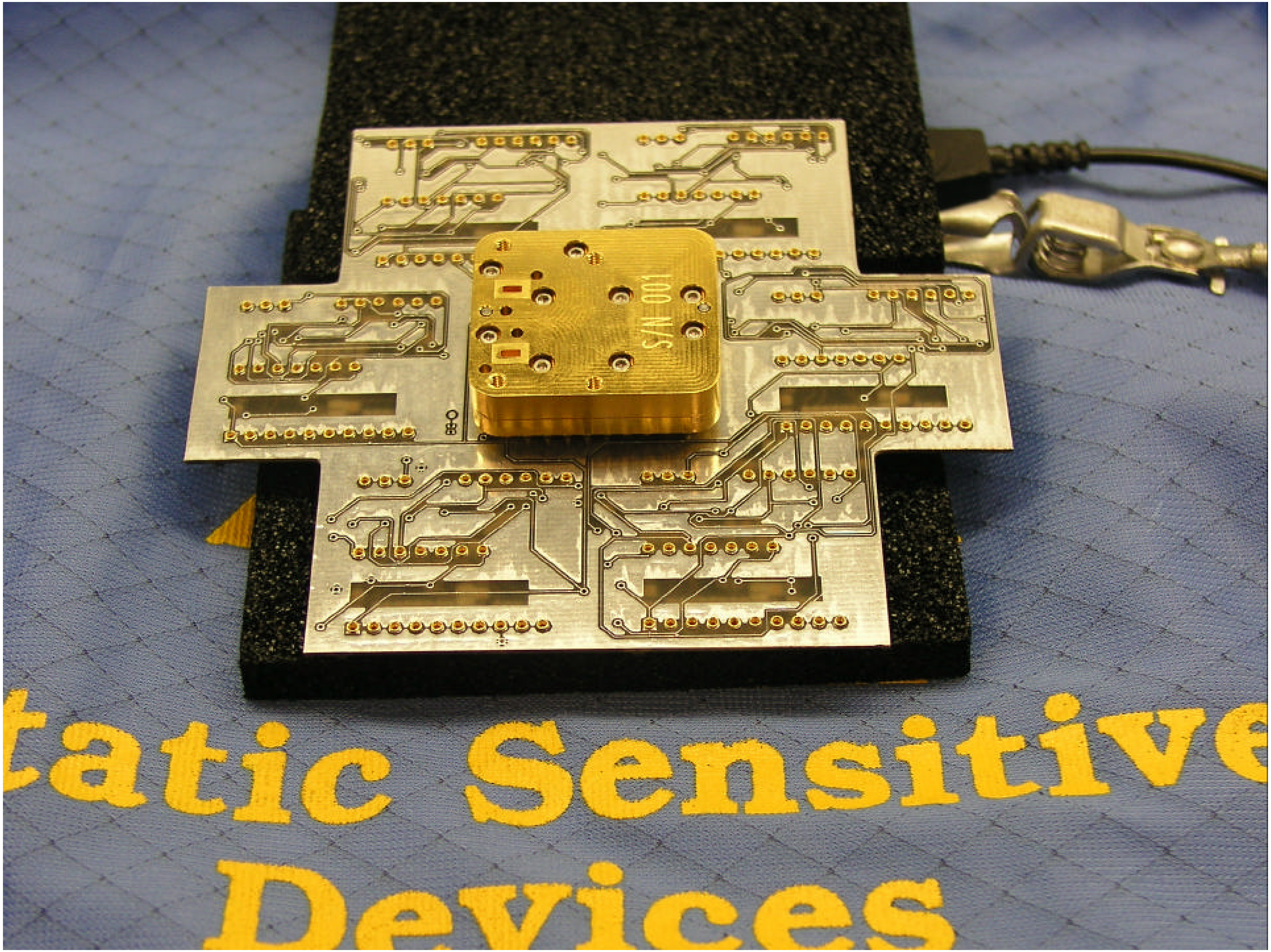
~18 inch

Radiometer on a chip, Automated assembly and optimization

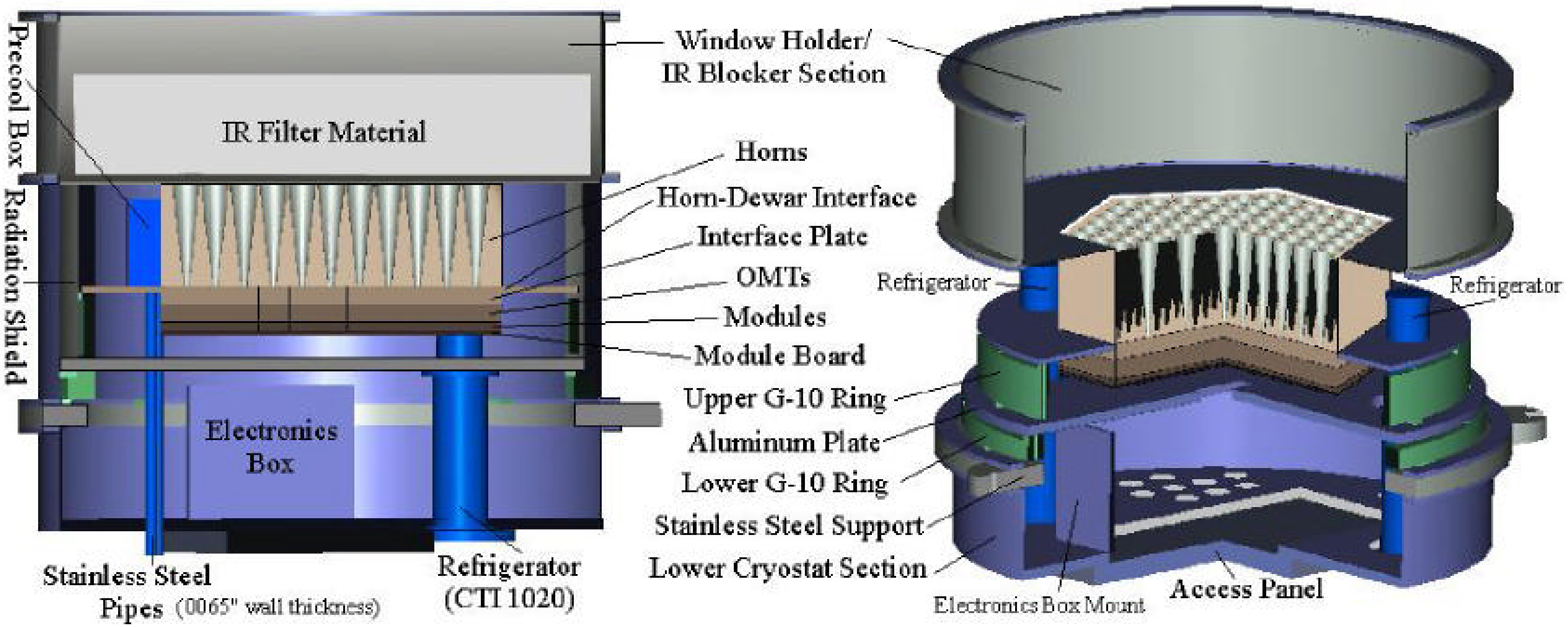


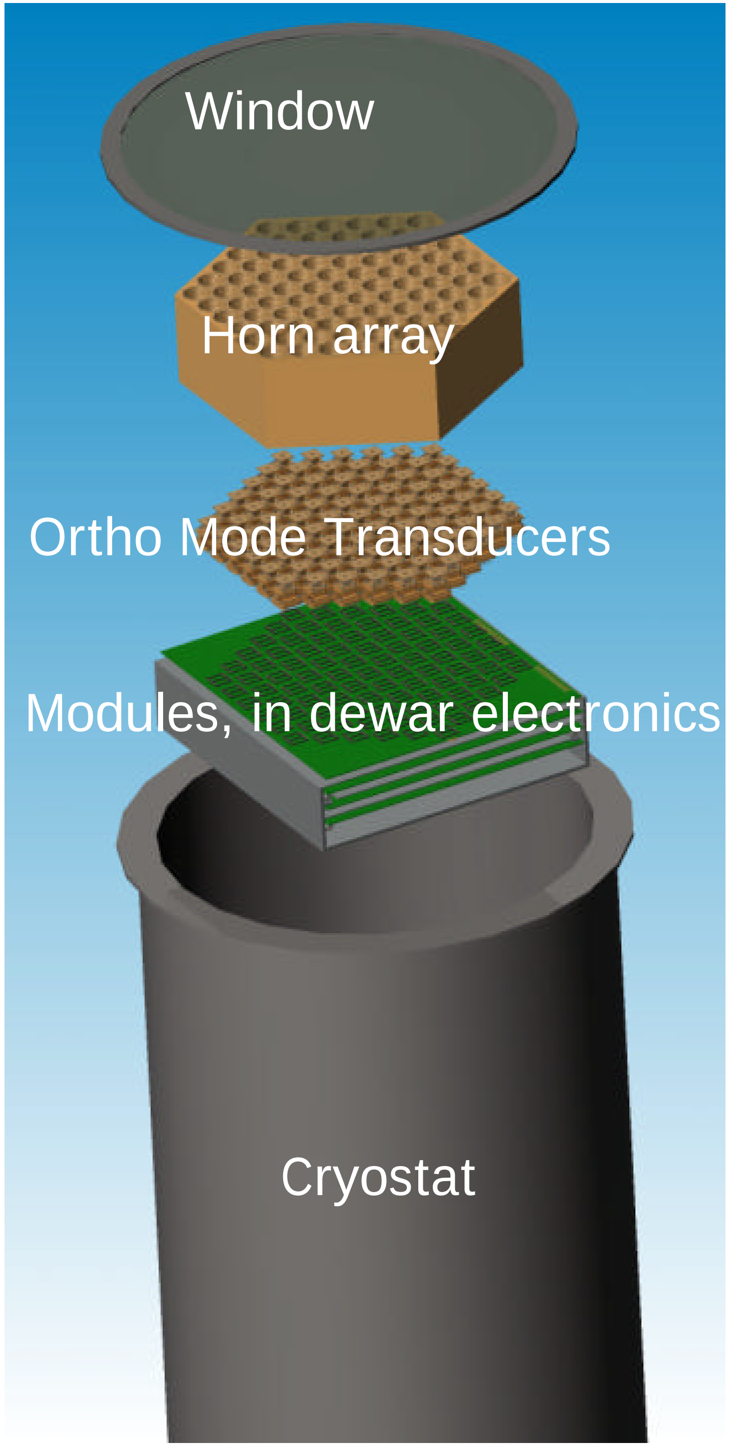
Radiometer on a chip




S/N 001
tatic Sensitive
Devices

The cryostat





Plans for QUIET

- Move 7m telescope to Chile
- Install three new 2m telescopes on CBI platform

91 W band elements
19 Q band elements

Phase I

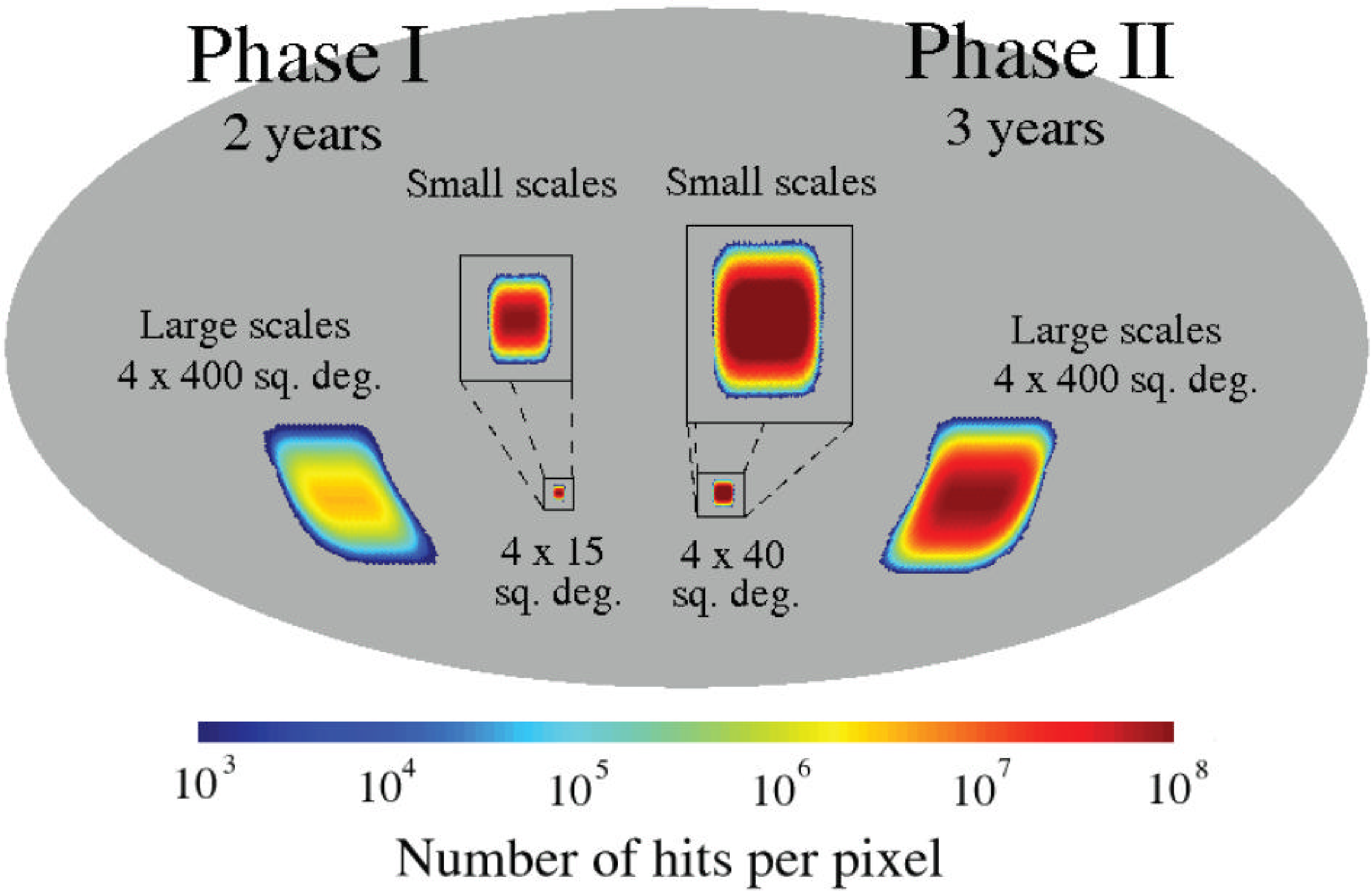
2x397 W band elements
2x91 Q band elements

Phase II

Observations at small and large scales!

The site (Chile, Atacama desert)

Sky coverage



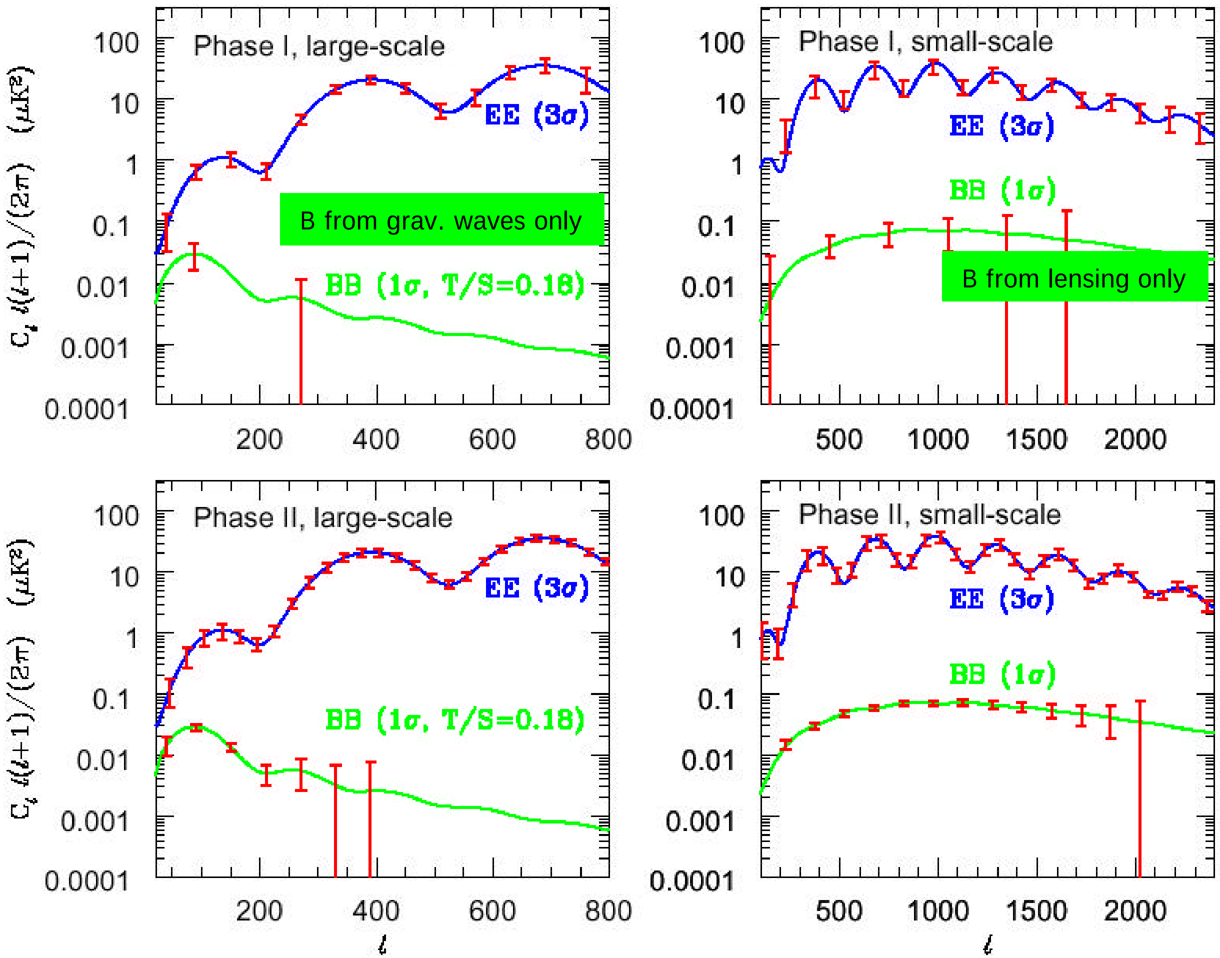
Expected Noise

Phase	Scale	Region [deg^2]	Noise/Pixel[a] [nK]
I	Large	4×400	400
I	Small	4×15	775
II	Large	4×400	85
II	Small	4×40	290

[a] W band. "Pixel" size is 1° for large scale, $0\overset{\circ}{.}1$ for small scale.

[b] Q band noise comparable on large scales, where a higher level of foregrounds is likely, and much lower on small scales, for $2.5\times$ larger pixels.

Expectation for QUIET



Simulations do take into account
- planned field of view
- realistic offset removal

Systematics to consider
- ➢ instrumental imperfections
  - phase differences
  - I->Q/U leakage
  - pointing error
  - beam asymmetries
  - ...
- ➢ ground pickup
- ➢ foregrounds

Expectation for QUIET

B-mode Physics

Phase	Lensing Power	Lensing Significance	ν Mass	Min. Detectable T/S
I	4.5σ	7.2σ	0.5 eV	(0.10)0.16
II	$\sim$25 σ	$\sim$30 σ	0.12 eV	(0.006)0.009

Comparable to future limits from double beta decay, close to mass scale expected from oscillations

Amplitude of gravity wave contribution, gets down to energy scales of 8 x10^{15} GeV

Already in Phase I measuring interesting physics!

Uniqueness of QUIET

- Only experiment that measures Q and U simultaneously in the same pixel
- Only experiment that measures at large and small scales
- Complements frequency coverage compared to bolometer arrays, important for foreground discrimination

Conclusions

- The CMB is a rich source for cosmological information
- Frequency spectrum and temperature anisotropy have been measured with good precision
- Many techniques developed to approach the challenge to measure the tiny polarization signal
- ‘First generation‘ of experiments started to get to the level of polarization
- Next generation under construction
- Exciting prospects for new insights to the very early universe